

Energy Research and Development Division
FINAL PROJECT REPORT

**A BUSINESS CASE STUDY ON
APPLYING SYNCHROPHASOR
MEASUREMENT TECHNOLOGY AND
APPLICATIONS IN THE CALIFORNIA
AND THE WESTERN ELECTRICITY
COORDINATING COUNCIL GRID**

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PREFACE

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ABSTRACT

A business case study for the use of synchronized phasor measurements was conducted. This technology can improve planning, operations, and maintenance of the power grid. The study demonstrated that the base hardware, phasor measurement units,, is a proven technology and that commercial implementation of selected applications is both feasible and desirable. Many implementations and demonstrations around the world, especially in California and the western United States, have verified the capability of this technology to provide information about fast-changing power system conditions.

The study analyzed major phasor measurement unit applications and their business and reliability benefits, assessed the status of development and deployment, and identified implementation gaps. This resulted in a roadmap and recommendations for a near-, mid-, and long-term process to transition PMU technology to full commercial application. This roadmap can serve as a foundation for other roadmaps developed by PMU users, and can guide vendors in prioritizing their development efforts by focusing on “more easily achievable” applications and system components.

Implementing a large-scale PMU system presents some unique challenges. Such systems need to transmit and store large amounts of data, and involve a large number of legal entities. For these reasons, this study also addresses how to successfully deploy a system for users with diverse requirements and varying needs.

Keywords: phasor, phasor measurement units, PMU, synchronized phasor measurements, Global Positioning System, GPS, power grid, software applications, monitoring, system architecture, large-scale deployment, transmission system, smartgrid, roadmap plan

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EXECUTIVE SUMMARY

Introduction

The North American electric utility industry has undergone significant changes since deregulation has taken place in many states. Systems initially designed and operated in a vertically integrated manner became subject to increased complexity with the inclusion of independent power producers, transmission companies, distributed energy resources, and market forces. This increased system complexity requires tools to address and understand the changing system dynamics. This was further intensified by economic pressures (for example, bankruptcy and insolvency) and the elimination of most research, development and deployment (RD&D) efforts at California's investor-owned utilities. The historic, longer-term focus on infrastructure, reliability, and the environment were replaced with the singular focus on short-term financials. This has resulted in reliability problems, congestion, and increased operations and maintenance (O&M) costs. Understanding short- to long-term needs (business, reliability, environment) and how promising technologies (such as synchronized pharos measurements) help with those needs requires creation of strategic roadmaps to utilize technology advancements and adapt to changing environments.

The United States Department of Energy (U.S. DOE) report to Congress (*Steps to Establish a Real-Time Transmission Monitoring System for Transmission Owners and Operators within the Eastern and Western Interconnection*, February 2006) found that:

- Technology currently exists that could be used to establish a real-time transmission monitoring system to improve the reliability of the nation's bulk power system; and
- Emerging technologies hold the promise of greatly enhancing transmission system integrity and operator situational awareness, thereby reducing the possibility of regional and inter-regional blackouts.

The technology referenced in the U.S. DOE report is synchronized pharos measurement units (PMUs). Many implementation and demonstration projects around the world have verified the capability of this technology to provide synchronized, time-stamped information about system conditions. At present, PMUs are the most sophisticated time-synchronized technology available for wide-area applications. This technology was made possible by advancements in computers and the availability of global positioning system (GPS) signals. One can foresee a future where high precision time-synchronization will be a normal part of any measurement.

California and other Western Electricity Coordinating Council (WECC) member systems have been worldwide industry leaders in realizing the potential of synchronized PMUs and in developing the first industry prototypes and applications. A challenge to

California, the WECC, and the industry is highlighting and promoting the key benefits of PMU technology and moving it from RD&D to commercial operation.

This business case study, while approximate given the large number and immaturity of PMU technology applications and their markets, provided useful insights to the expected commercial success and the societal and rate-payer value of the deployment and applications of PMUs. This study identified policy, economic, and financial barriers to commercial deployment, and identifies remaining technology gaps. It also provided information to help develop technology transfer strategies and educate potential users and policy makers on the benefits of these technologies.

The general terms *business case* or *business justification* are used throughout this report. These terms should be interpreted as an assessment of whether there is an economic rationale or justification for transmission owners, independent system operators, regulators and other transmission stakeholders to invest in PMUs and their applications. The business case or business justification for investing in PMUs would be that the increased reliability, operating cost savings, and other benefits exceed the costs of deploying the technology as part of an integrated network of PMUs at desired locations throughout the WECC.

The overall goal of this study was to analyze major existing and potential applications required to realize the reliability and financial benefits of PMU technology, identify deployment costs and barriers, and recommend steps to transition this promising technology to full commercial operation. The broader goal was to collaborate with stakeholder member organizations, transmission owners, independent system operators throughout the WECC, and others to expand the applications of synchronized phasor measurements and related technologies to improve reliability and congestion management, as well as provide other benefits for California electric rate payers. The primary objectives of the study were:

- Evaluating whether there is a business justification for deploying PMU technology throughout California and the WECC by assessing the benefits of various applications for electricity consumers, transmission owners, and other market participants, and by identifying present implementation gaps for those applications.
- Developing a plan for the deployment of PMU applications in the near-term (1-3 years), mid-term (3-5 years), and longer-term (5-10 years) and gain support for that plan from stakeholder groups at state, regional, and national levels.
- Developing business case guidelines that provide a methodology for evaluating the comprehensive benefits and costs of various PMU applications and gaining support from stakeholder groups for the methodology.

In support of these objectives, KEMA has performed a comprehensive study and analysis that determined the current state-of-the-art of various PMU applications,

potential new PMU applications, the potential infrastructure costs and gaps, and the expected benefits for use of the applications in grid operations. As a part of business case guidelines, the study generated quantitative examples of business benefits for selected applications based on utility data, primarily for illustrative purposes, but also to help draw general conclusions and recommendations.

Project Results

This study emphasized that synchronized phasor measurements will enable improvements in planning, operating, and maintaining the electrical grid that would otherwise not be possible. This study identified a large number of existing and potential applications (either already deployed or under development) of synchronized phasor measurement technology. Additionally, the study demonstrated that significant financial benefits may potentially be realized in using PMUs in market operations, such as more accurate locational marginal pricing-based clearing price calculations and improved congestion management through accurate detection of transfer capabilities. Some new applications have also been identified, such as real-time system model adjustment for fault location calculations and monitoring phase unbalance with state estimation applications. Details are presented in Appendix B and Appendix E. The study also concluded that as this technology is deployed and applied and as users gain experience and comfort, new applications will continue to be identified.

Although there are a huge number of potential applications, this study identified two key areas that would benefit from applying synchronized phasor measurement technology. The first is analyzing and avoiding outages that lead to catastrophic blackouts. Recent increases in blackouts (usually low-probability, high-impact events) have created questions as to the vulnerability, capacity, and operational management of the power grid. PMU technology is a paradigm shift that enables the higher levels of reliability improvement required for outage and blackout prevention. PMU applications improve early warning systems to detect conditions that lead to catastrophic events, help with restoration, and improve the quality of data for event analysis.

The second application is improving market and system operations. PMU applications help facilitate congestion mitigation through better system margin management. They also allow real time knowledge of actual system conditions as opposed to conditions defined by system models that may not reflect current conditions. In addition, state estimation solutions can be improved significantly for use in locational marginal pricing calculations, thereby improving the overall accuracy of the calculations and the associated energy clearing charges.

In addition to this general analysis, very detailed analysis of key individual applications demonstrated that many applications have a major improvement impact with PMUs or cannot be implemented without PMUs. These applications include angle/frequency monitoring and visualization and post-mortem analysis (including compliance monitoring). These are “more easily achievable” applications – those opportunities for

which needs are immediate, PMUs are required, infrastructure requirements are relatively modest, and products are available. Other applications that benefit from or cannot be implemented without PMUs include model benchmarking and outage prevention (including planned power system separation) and state measurement and real-time control. A detailed analysis of state estimation applications is discussed in this report. For other applications, non-PMU technologies are available; however, the deployment of PMUs allows additional benefits to be realized from using common data made available for the same investment.

These results serve as a base to develop a near-, mid-, and long term development and deployment roadmap. This roadmap and the process to transition PMU technology to full commercial application in California and the WECC are key outcomes of this study that should help California, the WECC and the overall industry benefit from PMU technology. As results are based on interviews with key stakeholders, this roadmap could serve as a base for individual user deployment roadmaps and could guide the vendors to prioritize their development by focusing on “more easily achievable” deployment applications and system components.

This study concludes that PMU applications offer large reliability and financial benefits for customers, society, and the California and WECC electrical grid if implemented across the interconnected grid. Therefore, it provides motivation for regulators to support deploying this technology and its applications. PMU technology is instrumental in improving early warning systems; developing System Integrity Protection Schemes (SIPS); detecting and analyzing thermal limits; improving angular, voltage, and small signal stability; promoting faster system restoration (including natural disasters); analyzing post-disturbance data; and more. For some of those applications (such as data analysis and angular stability warning), PMUs offer means and benefits not possible with any other technology. In addition, individual utilities could realize financial benefits if multiple integrated applications are deployed using basic PMU system infrastructure. These conclusions are based on a comprehensive analysis of various applications and related benefits. Concrete data on PMU system-related costs and financial benefits were obtained through interviews and industry experience with PMU implementation.

This study concludes that phasor measurement capability has advanced technologically to the point that commercial implementation of selected applications is both possible and warranted, and represents wise investment. Further, the implementation of this capability is necessary to reach the levels of grid operational management required for efficient use of the infrastructure currently in place as well as for future infrastructure enhancements. To gain the benefits offered by this technology, a coordinated effort among utilities, the California Independent System Operator (California ISO) and the WECC must be undertaken, with a coordination level beyond the present disparate activities. Without a system-wide approach, many of the capabilities and associated benefits will not be achieved. This will require a bottom-up approach from utilities in

defining needs and PMU applications and a top-down approach from system operators and coordinators to define an integrated infrastructure to optimize the benefits offered by the technology.

There is a need for vendors to fully develop and bring to market the applications in an RD&D phase and to develop new, promising applications. Vendors need both common system and common application requirements from users to be able to justify investments in new products. Considering the significant benefits for rate payers and transmission system reliability, regulators at both federal and state levels need to provide support for technology deployment. Also, the North American Electric Reliability Council (NERC) Electric Reliability Organization (ERO) should facilitate the required data exchange and certain system-wide levels of deployment that are required to achieve key application benefits.

Although working prototypes are proven for some applications and can be implemented with relatively small efforts, the lack of the technology's commercialization inhibits full-scale implementation. Operational and business processes and models have not been developed in most companies to address all of the issues associated with implementing this technology, which restricts the move to operational status. Further, additional focus on a system infrastructure (for example, at the Independent System Operator or Regional Coordinating Council level) to guide implementation in a consistent and coordinated manner should facilitate wider investment in and deployment of the technology.

For the U.S. Western grid and the industry to gain the benefits offered by this technology, a coordinated effort among utilities, the California ISO and WECC must be undertaken. The following process is proposed to the industry to speed up and minimize deployment costs:

- Each PMU user in the grid should develop a near-, mid-, and long-term application and technology deployment roadmap. This roadmap would include application requirements that would guide PMU installations and system architecture needs both locally and regionally.
- NERC ERO and/or WECC should champion the required data exchange and development of the overall system infrastructure. Based on individual user requirements, system architecture design, specifications, and deployment plans need to be developed. All users connecting to the overall architecture would need to fulfill key integration requirements such as hardware and software interoperability and data quality. It would also be beneficial to prioritize applications from the grid perspective.
- Develop uniform requirements and protocols for data collection, communications, and security through standards by such organizations as NERC, IEEE, and WECC. Engage vendors in standard development and provide

clear requirements for both accepted system architecture and industry application priorities.

- Provide adequate economic regulation and incentives that will justify deployment, which requires support by regulators.
- Each user should set up operational and business processes for installations, operations, maintenance, and benefits sharing. This requires creating projects with defined deliverables and deadlines; identifying asset owner, manager, and service provider; setting up procedures and rules; educating and training users; and facilitating culture change.
- Continue investing in RD&D through U.S. DOE, PIER, vendors, and users and promote developing and sharing test cases to develop new applications. Continue using pilot projects to gain experience and confidence.

Only by having all stakeholders contribute will this promising technology fulfill its potential for achieving financial and reliability benefits, which requires significant market penetration. This is dependent on vendors developing required products. A commitment from key stakeholders on planned PMU system implementation, including providing common application and architecture needs and requirements, should be communicated to the vendors so they can create their product roadmaps and minimize the high development costs associated with customized product development. Vendor roadmaps will guide development of key applications and system components that need to be implemented by a large number of users to enable a reasonable return on investment.

Because a large number of applications are in an initial development stage and there are potential new applications, it is necessary to continue investing in RD&D. A research and development roadmap by NERC/EIPP/Consortium for Electric Reliability Technology Solutions (CERTS) and a deployment roadmap from this study will help provide structured and consistent direction that will focus efforts, avoid unnecessary duplication, and optimize RD&D investments. In addition, the practice of joint pilot projects needs to continue.

Project Benefits

This study focused on California and WECC needs and requirements. Deployment of PMU technology among California utilities can provide cost-effective solutions to solve or minimize some of the problems faced by California and WECC grid users. The WECC power grid is spread across a large territory with significant power transfers over long lines. The grid faces congestion issues and is vulnerable to stability and inter-area oscillation problems.

PMU technology can provide solutions to meet California's needs, such as more accurate and comprehensive planning and operations tools; better congestion tracking;

visualization and advanced warning systems; information sharing over a wide region; improvements to SIPS; grid restorations; and other operational improvements that will result from experience with basic applications. The overall benefits will be a more reliable, efficient, cost-effective California and WECC grid operation resulting from better information and the ability to manage the grid dynamically, as opposed to reactive management in the face of unusual and potentially catastrophic events.

CHAPTER 1:

Introduction

World-wide disturbances and congestion have emphasized a need for a grid to be enhanced with Wide Area Monitoring, Protection, And Control (WAMPAC) systems as a cost-effective solution to improve system planning, operation, maintenance, and energy trading. Synchronized phasor measurement technology and applications are an important element and enabler of WAMPAC.

The Department of Energy (U.S. DOE) report to Congress (*Steps to Establish a Real-Time Transmission Monitoring System for Transmission Owners and Operators within the Eastern and Western Interconnection, February 2006*) finds that:

- Technology currently exists that could be used to establish a real-time transmission monitoring system to improve the reliability of the nation's bulk power system; and
- Emerging technologies hold the promise of greatly enhancing transmission system integrity and operator situational awareness, thereby reducing the possibility of regional and inter-regional blackouts.

The Western Electricity Coordinating Council (WECC) has been an industry leader in realizing the potential of the Phasor Measurement Unit (PMU) technology and developing first industry prototypes and applications. The first research-grade demonstration of phasor technologies was undertaken by U.S. DOE, the Electric Power Research Institute (EPRI), Bonneville Power Administration (BPA), and the Western Area Power Administration (WAPA) in the early 1990's. The system was effectively used to investigate causes of the major 1996 west coast blackouts. The U.S. DOE has continued to support outreach for these technologies, and has provided technical support to the WECC committees that rely on these data for off-line and model validation reliability studies. The Public Interest Energy Research (PIER) program supported research, development, and prototype-testing of a real-time dynamic monitoring system (RTDMS) workstation for offline analysis by California Independent System Operator (California ISO) staff in 2002. From 2003 through 2005, PIER supported the deployment of real-time phasor data analysis, voltage and dynamic stability assessment, and data visualization applications to monitor grid actual conditions, using wide-area phasor data from BPA, Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and (WAPA). These power companies have deployed PMUs in their systems, already realizing some benefits of phasors, particularly for near real-time disturbance analysis and modeling validation. BPA, PG&E, SCE, and San Diego Gas & Electric continue to develop new applications to fully utilize benefits of the PMU technology and all have projects (in conjunction with U.S. DOE and PIER funding) on PMU applications planned for 2007. For example, SCE and BPA have maintained a long-standing research, development and deployment (RD&D) programs on PMUs as a tool for real-time monitoring and control. This effort has shown the potential of this

technology to positively impact grid stability, outage avoidance and congestion management. One example of a direct benefit is SCE's Power Systems Outlook software, which is currently being used for post-disturbance analysis and will demonstrate its real-time display capabilities in the first quarter of 2007.

Recently, some large-scale phasor measurement deployment projects have been initiated, such as the Eastern Interconnection Phasor Project (EIPP) supported by U.S. DOE, and the Brazilian Phasor Measurement System led by ONS (the Brazilian ISO). EIPP will transition to the North American Electric Reliability Council (NERC) electric reliability organization (ERO) in 2007.

This business case study can provide useful insights to the expected commercial success, and the societal and rate-payer value, of research efforts in the deployment and applications of PMUs. This study also identifies technology gaps and the policy, economic and financial barriers to commercial deployment. It also provides information to help develop technology transfer strategies and educate potential users and policy developers to increase adoption of these technologies.

The goal of this study is to show stakeholders that the applications of phasor-measurement technologies by transmission owners and independent system operators (ISO) across the California and the WECC grid will lead to reliability, congestion management and market related benefits for California electric customers. Potential economic benefits include avoiding major system disturbances and blackouts which cost consumers several billion dollars per major incident, reduce congestion costs estimated to be approximately \$250 million per year in California, reduce cost and time to analyze power system events, and provide a means for quicker restoration following major grid outages.

Time synchronization is not a new concept or a new application in power systems. As technology advances, the time frame of synchronized information has been steadily reduced from minutes, to seconds, milliseconds, and now microseconds. At present, PMUs are the most comprehensive time-synchronized technology available to power engineers and system operators for wide-area applications. This technology has been made possible by advancements in computer and processing technologies and the availability of Global Positioning System (GPS) signals. We are rapidly approaching an era where all metering devices can be time-synchronized with high precision and accurate time tags as part of any measurement.

To achieve the benefits, advancements in time synchronization must be matched by advancements in other areas. One example is data communications, where communication channels have become faster and more reliable in streaming PMU data from remote sites to a central facility. Improvements in instrument transformers are important for the quality of the signals supplied to the PMU. A third area is in developing applications, such as, software that operates on the data provided by the PMU's. Academics, vendors, utilities, and many others have developed a large number

of methods and algorithms and performed system analysis and studies to apply the technology, but like any other advanced tool, PMU's are good only in the hands of trained users. For example, one of the proposed applications of PMU's is their use in control centers for monitoring, alarm, and control operations. The technology exists today to bring the PMU information into the control centers and present it to the operators in a user friendly graphical format.

A number of vendors are either offering or developing components, platforms, and applications for Phasor measurement systems. Technology components and platforms (such as PMU's, Data Concentrators, Data Acquisition systems, Communication Systems, Energy Management Systems [EMS], Supervisory Control And Data Acquisition systems (SCADA), Market Operations Systems, and so forth) required to implement and benefit from the synchronized phasor measurement applications are available. While a number of applications based on phasor data have been developed, there is a need for vendors to bring to production applications presently in an RD&D phase and to develop new promising applications. Since these applications are new and the business benefits have not yet been clearly defined, vendors need both system and application requirements from utilities to be able to justify additional investments in new products.

This study reviews in detail the technology, implementation issues, and potential benefits. The objectives of this study are to:

- Evaluate if there is business justification for investing in deploying the PMU technology in California and throughout the WECC through the assessment of benefits of the various applications for Electricity Consumers, Transmission Owners, and other market participants and identify the implementation gaps for those applications.
- Develop a deployment roadmap for PMU applications covering the near-term (1 year to 3 years), mid-term (3 years to 5 years), and the long-term (5 years to 10 years) and to gain support for that plan from stakeholder groups at state, regional, and national levels.
- Develop business case guidelines that provide a methodology of how to evaluate the benefits and costs of various PMU applications and to gain support from stakeholder groups for the methodology.

It is intended that the results of this study help various stakeholders (utilities, system operators, regulators, and vendors) to support, deploy, and develop PMU systems and applications. The deployment roadmap will help prioritize applications for deployment (short to long term), based upon their benefits to the users, cost of deployment and technology advancements.

Implementation of phasor measurement technology requires investment and commitment by utilities and system operators to install both individual devices and for

implementation on a grid level. The necessary investments include: planning, equipment purchases and upgrades, maintenance, resource allocation and training. For utilities and system operators to take a step toward system-wide implementation of phasor measurement technology they need to be supported by the regulators, WECC, and NERC. Requirements need to be identified for the overall system and selected applications that would benefit both the individual systems and the interconnected grid.

CHAPTER 2:

Project Approach

KEMA's approach to conducting this study was to assemble a team of leading experts in the field of phasor measurements; to locate, study, and understand the current body of knowledge on the subject; and, with the assistance of representatives from utility companies and other interested organizations, review the current state of the industry in terms of working prototypes and full scale applications, as well as identify future research and deployment plans. The team included some of the leading researchers in the field of phasor measurements from technical universities that are regarded as the most active and most advanced in the field. The participation by these representatives provided the project team with knowledge of the latest developments and an understanding of the outstanding issues needing to be addressed to further develop PMU applications. In addition to the resources from universities, U.S. DOE has supported a Pacific Northwest National Laboratory (PNNL) expert that has evaluated and summarized California and WECC Phasor Based Projects, Appendix A. The study also included research into the various vendor offerings at the present time.

The work process associated with this project began with an extensive literature search of the current research and applications of phasor measurement technology. An extensive library of technical papers, articles, and other literature was created and used by the project content experts in developing the applications reports found in detail in Appendix B of this project report.

Collaboration with industry representatives that are currently deploying PMU technology was an integral part of the project process. Interviews and workshops with California utilities that have deployed PMU technology were conducted as input to this study. Also multiple interviews and workshops with participants in the U.S. DOE sponsored Eastern Interconnect Phasor Project (EIPP) were conducted. The workshops and interviews also included representatives from organizations such as NERC and other regional and regulatory agencies, as well as vendors. A Business Case Evaluation Matrix, Appendix C, was used to collect information on industry needs, map importance of PMU to help with those needs, qualify investments required, and identify development/deployment status of individual applications. In addition, anecdotal benefits to illustrate some practical experiences by people interviewed have been listed in Appendix D.

In addition to the technical applications research, this study has focused on developing guidelines to build a business case for the PMU technology. This work has generated quantitative examples, Appendix E, primarily for illustrative purposes, but also to help draw general conclusions and recommendations. Significant focus was put on investigating the market operations aspects of phasor technology. Specifically, research was conducted on grid congestion and the resulting financial impacts, financial market responses to major outage events, locational marginal pricing models, operation of the

Southern California Import Transmission (SCIT), and other issues. This work was done to confirm how PMU applications may offer benefits to market operations through better quality data on grid conditions resulting in more efficient and cost effective market operations.

The above effort resulted in reaching conclusions and recommendations and creating the roadmap for commercial deployment of the technology.

Finally, an integral part of the project process has been the presentation and discussion of the project with the Policy Advisory Committee members, utility executives, and other leading stakeholders in California. These periodic meetings and interviews have provided valuable feedback on the project process and status and provided the project team with direction for the overall project.

CHAPTER 3:

Project Outcomes

3.1 Key Overall Benefits

Synchronized phasor measurements are the next generation of paradigm-shift technology, enabling improvements in planning, operating, and maintaining the electrical grid that would otherwise not be possible. This study has identified a large number of existing and potential applications (either already deployed or under development) of the synchronized phasor measurement technology. It is concluded that as this technology is deployed and applied and as users gain experience and comfort, new applications will continue to be identified.

It is expected that synchronizing measurement with high accuracy and using these measurements for various applications will become a part of the standard system planning and operations. If proper measures are taken (including an adequate investment mechanism) to achieve the benefits identified in this study, the expectations are that market penetration of this technology will grow rapidly.

Although a huge number of applications are expected in grid operations, this study has identified two key categories of applications that could benefit from the technology:

- Analysis and avoidance of outages, with extreme manifestations in blackouts
- Market and system operations

Both categories above share common application modules using a PMU system. For example, a PMU application module to detect angular instability condition and margins using angular stability analysis is beneficial for both avoiding outages and improving market operations (for example, better congestion management); improvements in State Estimation would benefit both preventing disturbance propagation and more accurate locational marginal pricing.

3.1.1 Avoidance of Outages

Recent wide-area electrical blackouts have raised many questions about the specifics of such events and the vulnerability of interconnected power systems. Historically, after each widespread cascading failure in the past 40 years, the power industry has focused attention on the need to understand the complex phenomena associated with blackouts. For example, major reliability improvements have been made after major blackouts events in the U.S. in 1965, 1977, and 1996. Within the last two years, as the power systems are again pushed closer to the limits, the number and size of wide-area outages has increased, affecting more than 150 million customers worldwide.

Although large-scale blackouts are still very low probability events, they carry immense costs and consequences for customers and society in general as well as for power companies. It is easy to misjudge the risk of such extreme cases. The high costs of

extensive mitigation strategies (for example, building new transmission lines), combined with inaccurate probabilistic assessments (blackouts will not happen in my system), have led to inadequate risk management practices, including not focusing on cost-effective prevention and mitigation initiatives. Such initiatives can provide value through avoidance of huge blackout costs.

There are two stakeholders that benefit from outage/blackout avoidance:

- The society/rate-payers, whose benefits can be quantified using methods that estimate the cost of blackout on the society and the economy (as described in Appendix E, Business-case study examples). Those costs are enormous. For example, society costs for August 14, 2003 blackout in the U.S. and Canada and for August 2006 WECC blackout were estimated at \$6 billion and \$1 billion, respectively.
- The utility company, whose benefits arise from avoiding cost of litigation, cost of service restoration, undelivered energy, and the negative impact on stock price and on valuable management time.

Utility stock price is affected by a blackout, although this impact may be temporary. In general, stock price is based on three factors: expected profits, expected profit growth, and perceived risk. With regard to risk for utilities, perhaps the most important aspect is regulatory risk since regulators ultimately determine the maximum profit that a utility is allowed to make. Blackouts, and a utility's response to blackouts, can materially alter perceptions of regulatory risk, and can significantly affect share price. Table 1 shows an example of stock movement after the August 14, 2003 blackout, showing the loss for the utilities involved in the blackout. A few days after the blackout, the stock price of First Energy slid further, by another 9.3 percent, although it recovered in few months.

**Table 1: Utility Stock Price after the August 14, 2003
Blackout for Utilities Involved in the Blackout**

Utility	Day Before	Day After	Change
First Energy	29.35	28.84	-1.74%
AEP	29.35	28.84	-1.74%
Con Ed	23.49	23.27	-0.94%
Detroit Edison	32.15	31.99	-0.50%
National Grid	29.92	29.53	-1.30%
Average			1.24% Loss

For utilities not involved in the blackout, stock price movement for the same days followed a more typical daily pattern of gains and losses with an overall average gain of 0.5 percent, as detailed in Table 2.

**Table 2: Utility Stock Price after the August 14, 2003 Blackout
for Utilities not Involved in the Blackout**

Utility	Day Before	Day After	Change
Pacific Gas & Electric	21.21	21.16	-0.24%
Edison International (SCE)	16.46	16.50	0.24%
Avista	14.44	14.52	0.55%
Xcel Energy	13.30	13.38	0.60%
Dominion	56.99	56.59	-0.70%
Progress Energy	36.89	36.85	-0.11%
TXU	20.29	20.46	0.84%
Duke	15.76	16.08	2.03%
Southern Company	26.32	26.24	-0.30%
Entergy	49.48	49.38	-0.20%
FPL	27.27	27.21	-0.22%
Scottish Power (PacifiCorp)	21.53	21.85	1.49%
Centerpoint	7.74	7.75	0.13%
Ameren	38.47	38.72	0.65%
Puget Energy	19.66	20.06	2.03%
Cinergy	31.65	31.94	0.92%
HECO	18.63	18.84	1.13%
Tampa Electric	10.82	10.84	0.18%
Average Performance			0.50% Gain

Synchronized PMUs, as a paradigm shift technology enabling implementation of WAMPAC systems, is necessary to improve grid reliability and reduce probability of blackouts and minimize their impact. The complexity of the grid operation makes it difficult to study the permutation of contingency conditions that would lead to perfect reliability at reasonable cost. An accurate sequence of events is difficult to predict, as there is practically an infinite number of operating contingencies. Furthermore, as

system changes occur, (for example,, addition of independent power producers (IPP) selling power to remote customers, load growth, new equipment installations) these contingencies may significantly differ from the expectations of the original system designers.

PMU technology is instrumental in improving early warning systems, System Integrity Protection Scheme (SIPS), detecting and analyzing thermal limits and angular, voltage, and small signal stability, faster system restoration (including natural disasters), post-disturbance data analysis, and so forth. For some of those applications (such as data analysis, angular stability warning), PMUs offer means and benefits not possible with any other technology.

3.1.2 Market and System Operations and Planning

Lack of investments in transmission infrastructure in last couple of decades has resulted in significant congestion costs. In the case of California ISO, congestion costs exceeded \$250 million in 2005. For day-to-day congestion management, actual flow on a line is compared to a Nominal Transfer Capability (NTC) based on thermal limitations, voltage limitations, or stability limitations. The assumptions used in offline NTC calculations may lead to unused transfer capability and lost opportunity costs in the dispatch process. The extent that excessive margins contributed to the total congestion costs is unknown. Congestion relief occurs through the ability to use actual transfer limits instead of conservative limits imposed due to angle and voltage constraints. PMU technology has been identified as either necessary (for example, stability limitations) or beneficial (for example, thermal and voltage limitations) in addressing this issue.

The intent is not to reduce transfer capability margins, but to accurately identify what dynamic, real-time margins are and act accordingly. If those margins are higher than margins calculated based on off-line analysis, there is a possibility to utilize them and, consequently, reduce congestion and associated costs. If it is found that the margins are less than calculated, the congestion costs would go up, but system reliability would be enhanced and potential outages prevented (see the previous section on avoidance of outages).

This study has uncovered a new area where PMUs could provide major benefits, improving accuracy of Locational Marginal Pricing (LMP). Although LMP is not currently part of the California ISO market model, it is expected to play a key role in the California ISO's pending market redesign.¹ The cost of energy injections and deliveries at each bus in the California ISO controlled grid will be set by an LMP equal to the sum of the marginal energy bid price, congestion costs and losses. For the purpose of Day Ahead (DA) markets and Hour Ahead (HA) markets, nodal prices will be calculated using offline power-flow cases. However, in the Real Time (RT) market, LMP calculations will use results of State Estimation (SE) runs performed each 5 minutes.

¹ California ISO is proposing to implement its market redesign or MRTU in 2007, subject to FERC approval.

These cases will then be used to calculate the marginal congestion costs and losses for each bus, which will be added to the marginal energy bid price to determine the real-time LMP at each node. This calculated value will be used for settlement with all providers and loads at each bus. Therefore, any error or noise in the SE solution will result in incorrect prices to customers and invalid price signals to the market. Implementing SE algorithms that include PMUs can improve the quality of the SE solution. Even slight improvements in SE accuracy could affect California ISO's marginal loss calculations and congestion cost calculations performed for calculating LMP in real-time. With approximately \$14 billion in energy charges clearing the California ISO market each year, even a 0.5 percent improvement in LMP accuracy could have a \$70 million impact on settlement costs each year.

Besides the use of PMUs to augment the inputs to the State Estimator and thus improve its output, PMUs can help in providing more accurate parameters for the grid model. The LMP Calculator can therefore calculate the actual LMPs as opposed to the estimated LMPs that come from using assumed values for the key system parameters. The difference in actual LMPs and SE-based LMPs can be significant and warrant its own investigation.

3.1.3 Overall Benefits for Industry and California/WECC

Poorly recognized dynamic constraints can endanger reliability and unnecessarily narrow operating limits and prevent optimal energy transactions, resulting in lost revenues. Deployment of a PMU system for better congestion and disturbance tracking, visualization, information sharing over a wide region, and protection and control in real time is essential to manage the grid more reliably and cost-effectively on a day-to-day basis, as well as in emergencies.

The WECC power grid, including California, is spread across a large territory with significant power transfers over long lines. The grid faces congestion issues and is vulnerable to stability and inter-area oscillation problems. These issues resulted in major blackouts in 1996 with further effect of de-rating of the power lines with ensuing financial losses to the grid users. California/WECC has initiated extensive measures to counteract those problems, such as extensively implementing automated Power System Protection Schemes (PSPS) designed to act during major disturbances and reduce the burden on the operators.

Deployment of PMU technology could provide cost-effective solutions to solve or minimize some of the problems faced by the California/WECC grid users by helping provide more accurate and comprehensive planning and operations tools, better congestion tracking, visualization and advanced warning systems, information sharing over a wide region, improvements to special protection schemes, and so forth. Some example benefits have been experienced by SCE, PG&E, and BPA even with a limited deployment of the technology.

3.2 Application Benefits

A goal of this study has been to analyze major applications to provide independent and objective analysis of business and reliability benefits of the PMU technology for various stakeholders with a major goal to help industry transition to full commercial operation. This study has evaluated state-of-the-art research, development and initial deployment of numerous existing and potential PMU applications grouped in 10 major categories. Although this study has tried to provide a comprehensive analysis of all major applications, as the applications area has not fully matured, some applications or variations of identified applications are not fully covered in the study. In addition, as PMU systems are becoming more widely deployed by utilities, it is expected that new applications will continue to be identified. The study has also identified some new applications and benefits, such as more accurate LMP calculations, monitoring phase unbalance with SE applications, and real-time system model adjustment for fault location calculations. Details are presented in Appendix B and Appendix E.

Various challenges related to deployment of applications have been addressed, such as:

- System architecture and data exchange needs
- Integration of PMU functionality in intelligent electronic devices (IEDs)
- Number and optimal location of PMUs

A large number of software applications benefit from time-synchronized data. Once the adequate PMU system is built, incremental costs of adding applications are minimal in comparison to the added value achieved. In addition, some of the major benefits of PMU application result from the system-wide applications (for example, avoiding major blackouts) that require PMUs to be installed and connected across utility boundaries. For some applications (for example, angular separation alarming on a situational awareness dashboard), benefits to an individual entity (for example, utility) are achieved only by having system-wide information. As a result of the above, a well-planned, system-wide PMU deployment, implementing optimal system architecture, is necessary to take a full advantage of the technology.

System architecture needs to be designed, specified, and implemented to serve present and future application needs for the whole grid. These are not easy tasks as requirements from a large number of applications, as well as a large number of users, need to be considered. Challenges with system architecture, including issues with integrated Intelligent Electronic Devices (IEDs) are described in Section 3.6, while recommendations on a process are described in Section 4.1, Recommendations and Key Success Factors.

The challenge related to determining the optimal locations for equipment is to support the broadest number of applications and uses. The marginal difference in data from one area of the grid to another as it relates to specific applications and potential problems must be evaluated to determine the required number and location of PMUs to support

the intended use. This requires development of an application deployment roadmap to guide deployment needs.

In general, for the reasons above, to transfer the PMU technology from RD&D to production, it is necessary for each user to create an application deployment roadmap that will guide PMU installations and system architecture needs. The following sections in this chapter represent a summary of 10 major application areas with focus on benefits and implementation gaps. More detailed description of each area is in Appendix B.

3.2.1 Real Time Monitoring and Control

Description

This application of phasor measurement technology facilitates the dynamic, real-time capture of system operating conditions. This information, provided to the system operator, allows for increased operational efficiency under normal system conditions and allows the operator to anticipate, detect and correct problems during abnormal system conditions. Compared to current EMS monitoring software that uses information from state estimation and SCADA over several second intervals, time-synchronized PMUs introduce the possibility of directly measuring the system state instead of estimating it based on system models and telemetry data. As measurements are reported 20-60 times per second, PMUs are well-suited to track grid dynamics in real time.

Phasor measurement technology is the only known technology that can offer real time monitoring application and benefit in three specific areas:

- **Angular separation analysis and alarming** – enables operators to assess stress on the grid. Measurement of phase angle separation allows early identification of potential problems both locally and regionally.
- **Monitoring of long-duration, low frequency, inter-area oscillations** – accurate knowledge of inter-area oscillations allows operators to adopt a power transfer limit higher than the limit currently in use.
- **Monitoring and control of voltage stability** – provides for a backup to EMS voltage stability capability.

Each of these three areas offer potential benefits and although each may not be ready for commercial implementation, the phased implementation of the capabilities of real time monitoring is feasible and provides for immediate realization of the “more easily achievable” elements.. Direct benefits to the utility are possible through these applications as outlined below.

Benefits and Status

Real time information of angular separation informs operators that they face imminent problems in their area and also provides the information to neighboring areas. This capability would have provided early indication of problems in northern Ohio in 2003. Additionally, angular separation data allows for correction of conservative planning

assumptions or operating limits developed from planning studies or off-line operational studies. The continuous monitoring and analysis of real time conditions facilitates operation of transmission corridors closer to their real stability limits without sacrificing confidence levels for secure operation. This directly impacts operating capacity and perhaps allows for deferment of upgrades or new facilities.

The detection and analysis of inter-area oscillation modes provides the capability to improve existing dynamic system models. In turn, increased confidence in system studies allows for optimization of system stabilizers and potentially the coordination of damping controllers with neighboring utilities. Net benefit again, as with angular separation, is the capability to increase operating limits and reduce congestion.

Monitoring and control of voltage stability offers benefits in the areas of congestion management and blackout prevention. Knowledge of actual voltage stability facilitates the transfer of more megawatts (MW) in a given corridor. The ability to prevent blackouts requires detailed system studies that use both dynamic and static analysis techniques. The system dynamics are not adequately tracked with currently available monitoring devices but can be captured with PMU technology.

There are varying degrees of commercial use of these monitoring capabilities. Experimental implementation of wide area monitoring has been accomplished in the United States, Asia, Europe and Mexico. In the United States, implementations in New York, Florida, Georgia and California have provided data for validation of models and further development of monitoring systems. The current Eastern Interconnection Phasor Project (EIPP) of the U.S. DOE continues to grow in participation and interest with the Tennessee Valley Authority (TVA) having developed an experimental monitoring system.

Beneficiaries of this application area are primarily: rate-payers, utilities, ISOs, and neighbor.,

Implementation Gaps and Costs

There is a huge difference in requirements for real time monitoring and real time control. As communication and data requirements for real time control are very demanding, initial deployment should focus on real time monitoring to gain experience and acceptance.

Two primary issues currently restricting wider implementation and use of PMU technology for real time monitoring in the control centers are availability of commercial computational tools and established process to use this information (including the studies required for optimal location of PMUs and training and cultural change). A gap exists between observing an oscillation (and alerting the operator) and translating it into a to-do-list for the operator. In an industry where reliability of operation is one of the most important criteria, skills and trust are developed through experience.

Implementation of PMUs for monitoring applications requires a training program that

includes clear explanations, real case studies, and carefully planned scenarios that will help the engineers and operators not only understand the technology but to trust the information it provides. For example, information that a critical angle is changing fast may only help an operator if clear procedures on actions required are provided. Generally, there is a lack of actionable information provided by existing software applications. Performing studies to determine the area of a particular network where the greatest issues of stability or congestion exist is not a difficult issue to overcome as the capability exists currently to do this.

The current data communications and processing capabilities also restricts wider implementation and use of PMU technology for real time monitoring. Data communications from the PMU to the user interface requires robust data concentration, management, and transfer capability that in many cases does not exist commercially today. While the basic data processing technology is available, the hardware and software to support data collected, processed and transferred for these applications is still considered developmental.

In general, vendors are not advancing rapidly in this area due to lack of immediate market applications. Users, on the other hand, are not pushing the vendors forward until some prototypes are proven.

A number of other less critical issues exist from one application to another and, in most cases, are specific to those applications. None of these issues are in any way insurmountable for real time monitoring as the knowledge and technology to overcome them exists today.

3.2.2 State Estimation

Description

State Estimation, a statistical analysis to determine a best possible representation of the system state based on imperfect telemeter data, is widely used in transmission control centers and ISO operations today to supplement directly telemeter real time measurements in monitoring the grid; to provide a means of monitoring network conditions which are not directly telemetered; and to provide a valid best estimate of a consistent network model which can be used as a starting point for real time applications such as contingency analysis, constrained re-dispatch, volt VAR optimization, and congestion management. State estimation has a number of ancillary applications with varying degrees of successful utilization in the industry such as bad data detection, parameter estimation, status estimation, and external model. State Estimation implementations typically execute at periodicities from 10 seconds to 10 minutes.

The inclusion of PMUs in SE algorithms is numerically/algorithmically relatively easy. A number of researchers have developed algorithmic refinements around the bad data detection and parameter estimation application of PMUs. PMUs have been included in at least one successful SE deployment (New York Power Authority [NPA]) and a

number of pilot installations are in progress. A pilot project between TVA, Entergy, PG&E, and Manitoba Hydro, with interest from SCE and BPA is under way. San Diego Gas and Electric (SDG&E) is pursuing a similar project.

There are three complementary approaches in using PMU technology with SE:

- Evolutionary solution, with improvements achieved by adding phasor measurements to existing SE measurement set and applying 'meter placement' methods to determine most beneficial PMU locations.
- Revolutionary (next generation SCADA), State Measurement solution with all PMU measurements provided. This approach would require massive PMU deployment (30 percent - 50 percent of buses), but would allow much more frequent calculations and would be a foundation for closed loop control.
- Equivalent solution to use PMUs is for ISO/Regional Transmission Operator state estimator applications to help represent boundary conditions for the utility state estimators.

In fact, the revolutionary solution will be a natural extension of the evolutionary approach as the number of PMUs installed continues to increase.

Benefits

Phasor measurements can benefit state estimators in several ways. First, another input measurement is available. This may or may not improve redundancy depending upon whether the PMU is deriving its phase angle from the same current and potential transformers as are used for measuring MW and MVAR, but probably improves redundancy in some sense. More importantly, the direct measurement of a state variable (phase angle) will improve algorithmic stability and convergence. In the case where sufficient PMUs are available to provide network visibility on their own (revolutionary approach), a linear estimator can be developed which is not iterative and a very high speed estimator becomes a possibility. The accuracy of the estimated line flows as compared to measured line flows will be affected dramatically by the accuracy of the PMUs.

The availability of PMUs in state estimation will no doubt enhance the ability of the estimator to detect bad data, if only by adding to redundancy. One related benefit may be to make the detection of topology errors more realistic.

Beyond the direct benefits to the state estimation, there are potential benefits to analytic applications which depend upon state estimation results. One notable example is congestion analysis and congestion costs in an ISO framework with nodal pricing. The congestion cost depends upon day ahead bids and scheduling as determined by network optimization and dispatch. That analysis depends upon operating limits for the various transmission facilities. If more accurate state estimation could be used to operate transmission closer to real limits, congestion costs could be reduced at the margin.

Estimates of the improvement are in the range of 1 percent to 2 percent of congestion cost.

Finally, a PMU derived SE opens the door to have a three phase or a three sequence state estimator. This possibility has not been discussed in the literature. The potential benefits of such an estimator could be to monitor phase unbalance – which could be symptomatic of grounding or equipment degradation.

Beneficiaries of this application area are primarily: utilities, ISOs, and rate-payers.

Implementation Gaps and Costs

Adding PMU data to the state estimation problem is straightforward mathematically and not complicated from a software perspective. Bringing PMU data back to the control center for the purpose requires either a data link to the PMU master or a way of getting the PMU data directly into the SCADA system – which would require an analog output from the PMU going into a Remote Terminal Unit (RTU), or preferably, the ability for the SCADA system to read the PMU directly via a data concentrator – possible for more modern SCADA systems but difficult for older (5 years +) ones.

The downstream benefits of having slightly more accurate/reliable state estimation in other applications does not require any modifications to those algorithms but would require modification of operating practices to use less conservative limits.

Given the existence of PMUs and their availability to the control center, the cost is negligible. The cost of a data link from the control center to a PMU master is also negligible.

3.2.3 Real Time Congestion Management

Description

This application of phasor measurement technology facilitates the ability to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through dispatch adjustments in a least-cost manner.

PMUs provide additional, synchronized, highly accurate system meter data that offer significant benefit through improved calculation of path limits and path flows. The higher scan rate and precision of PMU data will enhance computation of Real-time Transfer Capability (RTC), which in many cases will exceed the NTC (Nominal Transfer Capability) for the same path. PMU technology can also improve real-time congestion management through providing a more accurate state estimator solution of the real-time flow on a line or path.

The extent excessive margins contribute to congestion is unknown at this time; however, in 2005 the California ISO congestion costs exceeded \$250 million. Assuming only a small percentage of this cost is attributable to conservative margins that could be better managed with PMU capability results in an ongoing financial benefit of significance. In some cases, it may be identified that margins were too optimistic. Although, congestion

costs could increase as a result, accurate margins would improve reliability and prevent outages.

Benefits

Improvement in real time congestion management would benefit all stakeholders in the transmission grid, for example,, utilities, ISO, regional operations. Society at large also benefits through improved power flow and reliability even in times of maximum load and power transfer. For example, in August 2005, California ISO experienced a Pacific DC Intertie outage that required curtailment of 950 MW of firm load for 40 minutes (633 megawatt hours [MWh]) plus 860 MW of non-firm or interruptible load for 77 minutes (1,047 MWh). The curtailments were required to balance loads and mitigate congestion. Data from PMU tools on the potentially congested paths in such a case could reduce the need for such curtailments by providing operators with real-time data on the capacity of the system to move energy across specific paths.

Also, at a minimum, information from PMU tools would provide for verification of NTCs and support decisions on investment in additional capacity or in remedial measures.

Beneficiaries of this application area are primarily: rate-payers, utilities, ISOs, and power producers.

Implementation Gaps and Costs

The major issue is that no commercial grade applications for real-time congestion management currently exist. Development and testing of PMU based real-time rating applications have been conducted in a limited manner. A particularly promising field test has been conducted on a voltage stability constrained corridor between Norway and Sweden.

There is competition for this solution from other methodologies. Voltage/stability limits can be addressed through the use of fast pattern matching techniques to calculate limitations based on off-line studies. This method, while an improvement over the less dynamic techniques in use today, ultimately depends on the off-line studies developed for a given range of conditions that may or may not accurately represent actual system conditions. Only PMU-based methodologies will adapt to the existing system state regardless of whether or not that state has been previously envisioned and simulated in off-line studies. Further, there exist today a number of non-PMU applications to determine the real-time rating of thermally limited paths and one vendor offers a PMU based application for this use.

Costs of PMU technology for congestion management are estimated to be relatively low, approximately \$100 thousand per control center, once certain pre-requisites are in place. These include adequate system visibility through RTU and PMU hardware placement and incorporation of basic PMU measurements into the EMS/SE.

There are other issues of implementation for PMU based congestion management. The level of uncertainty regarding the number and concentration of PMUs required to achieve the desired level of improvement in state estimator solutions and on-line rating calculations is a primary challenge. Further, the length of time that will be needed for the power industry to adopt PMU based real-time calculations of transfer limits on congested paths is unknown and a major variable in attempting to quantify benefits. The cultural issue of operator acceptance must also be addressed through demonstrated accuracy and reliability of equipment and applications.

California and WECC should seek additional targeted opportunities to improve congestion management through PMU based applications, particularly on those paths where power deliveries are limited by voltage or stability constraints. In such cases it may be possible to improve the real-time congestion management process by the two-fold combination of (1) improved path flow calculations, and (2) increases in path ratings through real-time rating algorithms utilizing PMU inputs.

3.2.4 Benchmarking; System Model Validation and Fine Tuning

Description

The goal of model verification and Parameter Estimation (PE) is to identify questionable power system modeling data parameters (network, generator, load models, and so forth) and calculate improved estimates for such quantities.

In general, automated means are not available to build power system models. Therefore, model building tends to be labor intensive, subject to engineering judgment and human error. Furthermore, once an error enters the modeling database it is difficult to identify and may go undetected for years.

The implementation of phasor measurement based tools, methods and applications offer a means of improving models. By providing precise, time synchronized phasor measurements from various nodes in a power system, PMU deployment provides new opportunities for identifying errors in system modeling data and for fine-tuning power system models utilized throughout the industry for both on-line and off-line applications (power flow, stability, short circuit, OPF, security assessment, congestion management, modal frequency response, and so forth). Synchronized phasor measurements can be used to enhance the performance of Parameter Estimation (PE) algorithms currently incorporated into commercial energy management system (EMS) applications and to find and correct steady state modeling errors, for example, impedances, admittances and tap data. In Europe, a commercial application of PMUs currently computes transmission line impedance.

Use of phasor measurement for benchmarking and fine-tuning dynamic and oscillatory modeling parameters is more complex and less advanced than for steady-state models. A variety of Wide Area Measurement system (WAMS) applications are under

development using phasor measurements that may prove useful for model benchmarking and tuning of dynamic models. For example, Southern California Edison has dynamic and oscillatory mode analysis software capability in its Power System Outlook program to compare real-time measurements with simulated events. PNNL also has capabilities to analyze modal oscillations and compare simulated events with measurements.

Benefits

Model validation is one the primary utility benefit from phasor measurements. For example, actual measured nodal phasor values can be used to replace simulated values, thereby enhancing the performance of Parameter Estimation (PE) algorithms. This in turn improves the network model as the PE algorithm identifies errors in the models. In short, better and more precise data in gives better data out.

Validation of dynamic models is also facilitated by PMU recorded information. The best validation procedure for dynamic system models is through the recording of dynamic events by PMUs. The recorded events can then be compared to the response of the model for similar events and ultimately, the model parameters can be changed until it replicates the actual response recorded by the PMUs. Finally, fault locations can be more correctly identified through the PMU line impedance computation. The improvement in fault location allows for improvement in diagnosis and restoration of faults.

Beneficiaries of this application area are primarily: utilities and ISOs.

Implementation Gaps and Costs

Implementation issues for PMUs for model validation and benchmarking fall into two categories: steady state applications and dynamic model applications. For application to steady state models, phasor measurement technology would be a secondary use and benefit of a network of PMUs deployed for another primary use such as congestion management or real-time monitoring. In this context, the incremental issues are minimal, as are the costs. This is based on the assumption that the Parameter Estimation application is supported by the EMS in use in the area. Significantly higher costs would be incurred if this were not the case.

Applications using PMU technology for benchmarking of dynamic and oscillatory modes of system response need to be further developed and could take significant investments to move beyond RD&D. The potential benefits are large, especially if major forced outages could be avoided through model improvements.

The implementation of PMU based Parameter Estimation faces several gaps for widespread use.

- Lack of a systematic approach: The industry needs to develop a systematized approach for deploying PMUs for model validation and parameter estimation

- Need for commercial applications: Algorithms and methods that integrate PMU measurements into parameter estimation need to be commercially available.
- Need for additional field experience: Actual field data need to be available for model development and parameter estimation.
- Organizational issues: The confidence of system operators in the software tools and models is extremely important in taking decisive actions to operate the system during unusual events. Detailed PMU data used to validate and correct state estimator modeling errors can enhance operator confidence.

3.2.5 Post Disturbance Analysis

Description

The goal of a post-mortem or post-disturbance analysis is to reconstruct the sequence of events after a power system disturbance has occurred. The application of phasor measurements to this process offers potential benefit in the high degree of time synchronization that is available through the PMUs. Post disturbance analysis typically involves a team of engineers collecting and studying data from multiple recorders that are dispersed throughout the grid. The data recorders that have been in use in the industry for many years are not time-synchronized and therefore make the job of reconstructing the timeline of a disturbance a time consuming and difficult task.

Recently, Global Positioning System (GPS) technology has been used as a universal time source for various types of data loggers, including PMUs. The blackouts in the U.S. and Italy in 2003 were a major factor in the recommendation by authorities, such as NERC and U.S. DOE in the U.S. and Union for the Co-ordination of Transmission of Electricity (UCTE) in Europe, to deploy GPS capable devices. As more GPS time synchronization capability is deployed, utilities are finding that post disturbance analysis time can be reduced significantly.

The Northeast blackout of August 2003 was studied without the benefit of time-synchronized data. Over 800 events occurred during this blackout, most of them in the cascading failures between 16:06 EDT and 16:12 EDT. The magnitude of data from a four-minute period without synchronization reference proved to be a daunting reconstruction task for the investigators. A finding of the task force investigating the events was the realization that the analysis could have been much easier and faster with wider use of synchronized data recording devices. The analysis required 3 people spending 70 percent of their time on average for about 10 months. With the help of PMUs, the same analysis would take only 1 month with 3 people working full time.

WECC is making extensive use of post disturbance analysis. Data for various significant events is stored from various utilities and analyzed. Better tools are needed for post-disturbance analysis, however.

Use of PMUs for post-disturbance data collection and analysis does not have the same technical requirements as real-time applications; however, PMU installations for real-time data streaming can also be used for post-disturbance analysis.

Benefits

Based on the lessons learned from major blackouts, the primary benefit from having GPS synchronized data recording is to reduce the time spent on analyzing vast amounts of data. The time reduction can be from months to days or even hours depending on the volume of data. Some utilities currently using time synchronized data report that for more common events, such as transmission line faults, the time spent on sorting through events is virtually eliminated as the data is already synchronized.

Real-time data monitoring through PMUs, as outlined under that heading, provides the data record required for post-disturbance analysis but also provides the opportunity of observing system dynamics prior to events occurring. For post-disturbance analysis there is the additional benefit of having data from the period immediately before the event that may provide helpful clues in the event analysis. This in addition to the capability of recognizing, through real-time data, the potential for disturbance and the possibility of taking actions to avoid an event.

For disturbances that occur more frequently than a grid blackout, such as transmission faults, some utilities have reported that investing in a GPS-synced data-recording system is worthwhile:

“Before the [time synchronization system], we spent one to two hours every day rearranging the sequence of events. We can now perform disturbance diagnosis without spending any time on sorting through the events.

If we save two hours on fault diagnosis time, that’s two hours less time our customers have to go without power.”²

As the ability to synchronize data very accurately is not possible without PMU technology, accurate analysis of some fast, dynamic events may not even be possible without PMUs.

All the above benefits become even more pronounced with NERC and regulatory compliance monitoring requirements. Ability to document and analyze disturbances and quickly respond to public inquiries has both tangible and intangible benefits.

Beneficiaries of this application area are primarily: utilities, regulators, and ISOs.

Implementation Gaps and Costs

² “Southwest Transmission Power Implements GPS Time Source to Synchronize Substations,” T&D World, January 2006.

The cost and complexity of installing PMUs for post-disturbance analysis is low. This is because this application of PMU technology does not require real-time data streaming and the associated communications infrastructure. Data can be stored in substation computers for retrieval as needed. Examples are the logging devices in use in Europe since 1998. These devices are GPS time-synchronized and are read remotely. Data from these devices were used to analyze the 2003 Italian blackout.

Other devices are currently available to perform time-synchronized data recording of system disturbances. They include digital fault recorders, dynamic swing recorders, and sequence of event recorders. In some cases these types of recorders may be more effective than PMUs. The overall benefit of PMUs, however, is in the capability to compress and store large amounts of data over longer time periods and the ability of PMUs to capture trending events that occur over long periods of time. The other recorders are usually triggered by events and therefore miss the system data immediately preceding an event. Data loggers have improved in size, cost, data resolution and storage making their use more economically feasible than in the past. GPS time synchronization can also be achieved with data loggers although not to the same accuracy as with PMUs.

The primary barrier to widespread implementation of PMUs for post-disturbance analysis is the development of supporting software to further streamline the data analysis after events. While not a necessity, the increasing amount of data collected and stored through technology leads to a higher need for automated tools to process data. This need is not unique to PMUs, however, phasor measurement capability at this time somewhat exceeds the industry ability to manage the data.

3.2.6 Power System Restoration

Description

Standard operating procedures at most utilities define the steps to be followed for system restoration after an event. These procedures are generally based on some standard set of system conditions and associated operating parameters, which may or may not exist at the time of the incident. The dynamic nature of the power system, particularly following outage or unusual events, creates the risk that the conditions on which the operating procedures are based may not exist at the time restoration efforts are undertaken. PMU measurements, therefore, can provide a valuable input into the decision processes, as the measurements are real-time quantities that give the operators current information on system status.

One of the potential applications is an extension of the real-time monitoring and control application in that phase angle measurement is a primary parameter used in power system restoration procedures. During power restoration, system operators often encounter an excessive standing phase angle (SPA) difference across a breaker, which connects adjacent substations. By using the PMUs to monitor such a phase angle directly, the operators can make proper decision about when to close the circuit breaker

without damaging equipment or risking grid stability. In addition to risk mitigation in the restoration process, PMUs can also help reduce the time needed for system restoration.

Benefits

The primary benefit of PMU technology in power system restoration is the ability to provide operators with real-time information about the phase angles in relevant parts of the grid. This information helps the operator with critical decisions about timing, sequences, and feasibility of prospective restoration actions. In that respect, phasor measurement technology can expedite restoration and reduce the blackout time.

PMUs can also provide thermal monitoring of a tie-line thereby giving operators information on how long the tie-line can be relied upon in the restoration process before other actions may be required. Similarly, interconnection of distributed generation can be monitored to ensure that the DG unit(s) can safely be brought on line.

PMUs are currently in service for this application in some locations. An often cited example is the installation of PMUs following the Italy 2003 blackout. Review of the sequence of events showed that phase angle information was not known when operators were attempting to restore the initial line outage. Significant time was lost in attempts to restore the line ultimately resulting in overloads on other lines, which in turn tripped and caused the Italian system to blackout. Analysis showed the phase angle settings of the synchro-check relay were being exceeded, information that PMU measurement would have given the operators.

Beneficiaries of this application area are primarily: rate-payers, Utilities, ISOs, and power producers

Implementation Gaps and Costs

Phase angle monitoring is a commercial application of PMUs that is currently available. The issues associated with implementation of the application are cost, data communications and display of data on existing operator consoles. As outlined in the real-time monitoring summary, data communications can be an issue for large, integrated applications but is not considered a problem for phase angle monitoring.

Another issue to be considered is commercial competition for this application. Synchro-check relays are considered a competing technology as they have the capability to monitor phase angles and frequency and voltage on either side of an open circuit breaker. The preset parameters of the relay will determine if it is acceptable to close the breaker under the measured conditions. While adequate for this application, these relays are considered to be single-purpose devices and therefore quite limited in scope and usage when compared to PMUs.

This example highlights one of the challenges for implementation of PMUs in general and specifically for this application. Operators must be well trained and become

confident with the equipment and information they would receive from phasor measurements. New technology providing new information is a circumstance that will take an adjustment period to become fully utilized and for benefits to be fully realized.

3.2.7 Protection and Control Applications for Distributed Generation (DG)

Description

Growth of distributed generation (DG) and microgrid projects is expected to continue and to increase as more legislative action mandating renewable portfolios occurs. The pricing trends, opening of the competition in the electricity retail business, and convenience of having generation resources close to load centers will drive further proliferation of DG technologies. Distributed generation creates challenges for utilities it interconnects with in terms of protection, control, monitoring and safety.

While providing many benefits in enabling local access to generation, improving (potentially) reliability and providing some of the ancillary services such as frequency responsive spinning reserve, local voltage regulation, sag support with energy storage, power leveling and peak shaving, congestion management, and power flow control, distributed generation has not yet evolved to the point where transmission networks are with respect to large scale utility generation. Potential problems of interconnection with utility grids include, among other things, forced islanding of the DG in case of disconnection from the main source of supply and coordination of protection. Development of standards for interconnection is progressing slowly due to a number of issues, including the sheer number of parties that are taking active roles in the process.

Interconnection standards are also inhibited by the wide variety of DG designs and technologies. Issues include, but are not limited to, system impacts and analysis, DG penetration levels, safety, operation, reliability, various liabilities, allowing fully autonomous remote operation, and integration of control and protective relaying functions. The strongest support PMUs could provide in such an environment would be in control and protection.

The issue of islanding is of primary concern to utilities because of the inherent safety and operational problems an islanded DG system could create. Islanding of a DG system occurs when a section of the utility system is isolated from the main utility voltage source, but the DG continues to energize that section. A number of both passive and active control schemes have been devised over time to detect islanding. Utilities, standards-making bodies, and power conditioning system manufacturers have a common interest in determining the method that detects islanding most reliably.

An additional consideration is that the evolution of DG and increased proliferation is likely to create desirability for allowing islanding. Such action would promote a single DG or a group of DGs to operate in a multibus microgrid structure, where many of the functions and requirements of the transmission networks, would also be needed and where PMU monitoring and information infrastructure may be beneficial.

Proper operation of a microgrid requires high performance power flow and voltage regulation algorithms both in grid-connected and islanded modes. PMU technology seems very promising in monitoring DG and micro grids in both modes. However, low-cost design will be needed for broad market penetration.

Benefits

PMU technology for DG applications has potential benefits for utilities connected to DG sources, owner/operators of DG, and ultimately to all consumers through better integrated use of DG. Benefits fall into the areas of:

Control: PMU technology can provide the foundation for solving technical difficulties associated with the monitoring and control of a significant number of micro sources.

Operation and investment: The multiple DG sources that may exist behind a single utility interface in a microgrid can be optimally coordinated through real-time state information from PMU technology. The dynamic coordination of microgrid sources can be used for Volt/VAR support, congestion management, loss reduction and other operating needs.

Power quality/reliability: Increase in reliability can be achieved if DG is allowed to operate autonomously during transient conditions, especially when the source of disturbances is upstream in the grid. PMU facilitated coordination can allow a microgrid to continue to operate in island mode until the utility grid disturbance is resolved. Likelihood of complete blackout conditions is thereby substantially lessened.

Beneficiaries of this application area are primarily: independent power producers, utilities, and regulators.

Implementation Gaps and Costs

The number of DG designs, installations and interconnections with utilities creates a large variable in the design of PMUs for DG operations. As PMUs and the associated applications are presently being designed for transmission network operations, it is likely that the same designs will not be adequate for microgrid operations. Different models and applications will need to be developed for large scale, low-cost implementation in the DG market.

As the cost of interconnection protection and control can represent as much as 50 percent of the total DG project cost, a cost competitive PMU solution will have high interest. Distributed generation installations, especially small capacity systems, are extremely cost sensitive operations that do not enjoy the economies of scale of larger generation systems. With the current state of the industry in applying PMUs to transmission networks being in its' infancy, it is unlikely that PMU technology for DG applications will be developed with any urgency.

The benefits of this application can be realized as proven through some field trials. A prototype system has been proven capable of detecting islanding conditions with as little as 1 percent power imbalance. Traditional frequency based systems typically require 4 percent imbalance or more for detection. The desire of many regulatory jurisdictions to increase the amount of DG in a utility portfolio will be a primary driver in the development of PMU technology for this market.

3.2.8 Overload Monitoring and Dynamic Rating

Description

Standard loadings on many overhead transmission lines in the U.S. are based on conservative criteria to avoid overloads. Easy-to-use, cost-effective technology to enable real-time monitoring and dynamic rating of transmission lines has a major potential to avoid overloads and optimally utilize transmission lines. Line capacity is limited by performance of the conductor at high temperature and by safety standards that specify the minimum ground clearances. The use of PMUs can offer some degree of monitoring at a high time resolution. Although PMU-based systems for overload monitoring and dynamic rating cannot match the features offered by existing equipment monitoring systems, an advantage is in that the same PMUs can be used for other purposes.

There is a commercially available application based on PMUs for the monitoring of overhead lines. With PMUs at both the ends of a line, the resulting measurements allow calculating the impedance of the line in real time. The direct use of this is to estimate the average temperature over the length of the conductor. This method, however, does not provide information about hotspots, conductor sags or critical spans.

PMUs are well-suited, and commercial applications exist, for measuring impedance of a transmission line. One vendor takes this concept one step further by observing the resistance of the line connecting the substations in real time. The line resistance can change due to ambient and loading conditions. Knowing the characteristics of the conductor, an estimate of the conductor temperature can be made from the line resistance. The line being monitored by the pair of PMUs must have no line taps or substations in between. Another limitation is that the output of the method represents the average temperature along the conductor length. The advantage with the PMU-based method for monitoring a line is its low cost, relative ease of installation and use for other purposes. For example, the line impedance generated as a by-product can improve the accuracy of fault-locating algorithms.

Benefits

Line impedances are usually estimated based on line length, tower height, conductor size and spacing. Their Ohmic values are rarely verified. The PMU technology allows tracking the line impedance in real time, and thus helps improve any application (traditional as well as new) that makes use of line-impedance data.

For California, the benefits from overload monitoring and dynamic ratings of overhead transmission lines have been analyzed in a PIER study. We recite some key figures here:

- 2 percent to 5 percent increase in the power transfer capabilities of the existing grid.
- 20 percent to 30 percent improvement in the transmission efficiency of existing lines that are limited by ground clearances.
- 15 percent to 25 percent reduction in the need for acquisition and construction of additional right-of-way and the associated environmental impacts.
- Deferral of capital expenditures of \$150 million to \$200 million for the construction of new transmission lines in the next 10 years.
- Long-term or permanent deferral of capital expenditures of \$70 million to \$90 million per year for reconductoring projects.
- Short-term deferral of capital expenditures of \$8 million to \$12 million per year for reconductoring projects.

While we do not expect a PMU-based system for overhead line monitoring to deliver all the quantified benefits listed above, we believe that the PMU technology can provide additional inputs to the decision process related to transmission lines. For example, the transmission owner installs specific devices such as Sagometer™ to monitor critical spans (details) and PMUs at the two ends of the line to monitor the whole length (averages).

Beneficiaries of this application area are primarily: rate-payers, utilities, and ISOs.

Implementation Gaps and Costs

The cost of implementation is very modest as only a pair of PMUs is needed for each line. The installation is similar to that for a relay at a substation, and does not involve clamping or attaching devices on overhead spans or transmission tower.

There have been at least two known installations of PMUs for the purpose of overhead line monitoring. A field comparison of several technologies has been done for a line in Switzerland. This was the line that initially tripped and triggered the onset of the 2003 Italian blackout. Even though these technologies seem to produce consistent results for a relatively low temperature range, it is difficult to (a) have an absolute benchmark, and (b) translate the temperature information into sags.

One issue that remains to be verified with the PMU-based approach is the impact of instrumentation errors on the results. This is especially true for short lines (30 miles or less) where line resistances are already small to begin with. Even small errors in instrumentation (voltage and current) may generate relatively large percentage error in the calculated resistance, and thus the estimated conductor temperature.

The PMU-based system for overhead line monitoring is still largely untested. The commercial product, namely Line Thermal Monitoring from ABB, has been installed at two locations in Europe. The output, which is merely conductor temperature, has not been used in any decision-making process.

3.2.9 Adaptive Protection

Description

Adaptive protection is a philosophy of protection design that provides for adjustments in protection functions, automatically, as system conditions change. In short, the protection scheme adapts, within defined parameters, to prevailing system conditions unlike conventional protective systems that respond to faults or abnormal events in a fixed, predetermined manner.

Digital relays have two important characteristics that make them vital to the adaptive relaying concept. Their functions are determined through software and they have a communication capability, which can be used to alter the software in response to higher-level supervisory software, under commands from a remote control center or in response to remote measurements.

Though exact financial impact of adaptive protection using PMU measurement versus traditional protection schemes is difficult to quantify and varies from scheme to scheme, some of the benefits of adaptive protection using PMU measurement can be identified. Some examples are improved reliability balance between security and dependability of a protection scheme and better utilization of power generation, transmission and distribution equipment capabilities.

The protection applications that are identified as best suited for use with PMUs are out-of-step relays, adaptive line relays, adaptive security and dependability, adaptive reclosing, and fault location. In each of these applications, introduction of PMU data offers either new functionality or enhanced operation of existing relay functions.

Benefits

Some benefits resulting from adaptive protection are improved operations for the utility including improved reliability of a protection scheme, and better utilization of power generation, transmission, and distribution equipment.

Out-of-step relays: Actual angle measurements can be provided such that during a transient swing, a fast and accurate determination can be made regarding breaker operation for stable or unstable swings.

Adaptive line relays: The use of PMUs for other reasons provides incremental benefit in improvement of line relaying. PMU line data provides information that will improve existing relay solutions for certain primary protection issues associated with multi-terminal lines, series compensated lines, and parallel transmission lines to name a few.

Adaptive security and dependability: Phasor measurements can be used to determine when to alter the security-dependability balance in protection scheme. The redundant primary protection in existing protection systems clears virtually all faults, with the expense of some false trips. As false trips have been shown to contribute to large disturbances and allow cascading, an adaptive scheme triggered by system stress, could alter the relaying logic to ensure that false trips are avoided. This greatly reduces the possibility of cascading failures thereby increasing system reliability.

Adaptive reclosing: Phasor measurements provide the necessary input to ensure that a breaker recloses into only phase-to-ground or phase-to-phase faults and avoid reclosing into multi-phase faults.

Fault location: PMU technology allows tracking line impedance in real time, and thus helps improve any fault locations application that makes use of line impedance data.

The PMU technology could help reducing excessive generation trips used presently in WECC. The schemes could use phase angle separation as an input to determine generation drop levels.

Beneficiaries of this application area are primarily: utilities, ISOs, rate-payers.

Implementation Gaps and Costs

Implementation of phasor measurement capability can improve and enhance existing protection schemes. There are, however, several hurdles to overcome to fully implement adaptive protection using real-time PMU data.

Standards: Adaptive protection applications would require consistent dynamic performance of all PMUs. Currently there is no specification for dynamic performance tests for PMUs although IEEE standard C37.118 has recommended a standard be developed. The EIPP Performance Requirement Task Team is developing a guide for calibration standards and testing procedures (including dynamic) to assure performance and interoperability.

Communications network: The dependability, integrity and priority of communications to support adaptive relaying have traditionally been a concern among relay engineers. Back-up communications certainly and perhaps dedicated channels are required. Overall dependability and quality of service for relaying signals must be ensured.

Algorithm and field experience: Most adaptive line protection schemes are in research projects. Real world application requires field testing and associated modifications and enhancements.

Acceptance: Issues of back-up communications, relay setting errors, service availability while changing settings, bad data response are a few of the items that concern engineering and operating personnel and therefore create a challenge in general acceptance of the technology. The technical issues are not insurmountable and need

resolution; however, the issue of acceptance is more a cultural challenge than a technical challenge.

Cost: If communication support is already available and the protection device itself has built-in PMU measurement capability, then there is no cost associated with implementing the adaptive schemes described above. If PMUs are installed as separate dedicated devices, then there is a technical and cost issue for protection devices to communicate with and utilize the PMU measurement. In practical applications, protection devices and other applications sharing the PMU measurement may be a cost-effective solution to this issue.

3.2.10 System Integrity Protection Scheme, Including Planned Power System Separation

Description

Direct utilization of PMU data may improve system performance when used with current methods for planned system separation and other System Integrity Protection Scheme (SIPS). The planned separation of a power system into different segments – islands – is the action of last resort when the power system is undergoing unstable system conditions (such as thermal, angle, voltage, frequency), and a separation is unavoidable. Under these circumstances it is desirable to create electrical islands and separate them from the grid on a planned basis rather than an unplanned basis, and then reconnect them with the grid later when conditions for such action are favorable. Ideally, each island should have an approximately balanced generation and load, though in practice this may not always be the case.

System separation under these conditions is accomplished using System Integrity Protection Scheme (SIPS) often called remedial action schemes (RAS) or if only the local angle is considered, out-of-step relaying. These schemes are designed based on pre-calculated system behavior upon assumed state of the system: loading levels, topology, planned and unplanned outages, and so forth. In many practical situations the prevailing system conditions are quite different from those upon which the protection scheme settings are based. Consequently, the performance of these systems may not be optimal for the existing system state.

The use of PMU measurements instead of pre-calculated scenarios would improve a planned system separation in two key areas: (1) whether a power system is heading to an unstable state and among which groups of generators the loss of stability is imminent will be determined more accurately with real-time measurement, and (2) islanding boundaries could be determined dynamically according to the prevailing system conditions.

The use of real-time positive sequence voltage and current measurements provided by PMUs offers for the first time the ability to take note of what is happening on the power system at any moment, and by tracking the actual system behavior, determine if a planned separation of the network is necessary to avoid a catastrophic failure.

The application of PMU measurements to perform planned system separation on systems which are peninsular (such as Florida-Georgia or remote generators feeding a large power system) has been shown to work quite well. However, when the power system is tightly meshed – as is the case of the California and WECC network, no such real-time applications have been implemented. However, several research ideas have been discussed in the literature.

Benefits

Though exact financial impact of a successful planned system separation versus an uncontrollable system disintegration (or a planned system separation with existing control and protection schemes) after a large system disturbance is difficult to quantify and the results vary from case to case, the major benefits of planned system separations using PMU measurement are clear. These include minimizing lost revenues and reducing generator restarting cost for utilities, and limiting the direct impact to customers.

The pay-off of a completed and successfully implemented scheme in terms of fewer service interruptions, and higher power transfer limits (where those were limited due to pre-calculated stability imposed conditions) would be substantially greater making the application well worth pursuing.

Since a SIPS system using PMU measurement does not require extensive system studies to determine upon which assumed system conditions that the system should initiate a system separation, an added benefit is the saved manpower and time involved in such studies.

Beneficiaries of this application area are primarily: rate-payers, utilities, ISOs, power producers.

Implementation Gaps and Costs

The planned system separation using real-time PMU measurements and other SIPS hold the promise of greatly improved performance of such a scheme. The choice of locations where PMUs must be placed is relatively simple. SIPS are well entrenched in the California WECC system, and have been accepted by the system operators. Adding PMU measurement should still require extensive demonstration before it is accepted.

Implementation requirements depend on type and complexity of the scheme and the role of PMU measurements. If PMU measurements are added to the existing SIPS to improve and speed up instability detection, requirements are well within the scope of present technology. However, requirements for implementing a very fast and accurate system-wide separation scheme are more demanding. The data must be communicated to a central location, where a data concentrator and application processor must be located. In all likelihood the communication must be handled by dedicated fiber optic channels so that data latency can be limited to about 20-50 milliseconds. The implementation of this system would call for hundreds of PMUs to be installed with a

need of a communication infrastructure to support the large amount of real-time PMU data transfer.

The implementation would need a central control system to support the system able to process data from hundreds, and possibly thousands in the future, PMUs in real-time and issue control commands based on the real-time detection/prediction of system instability. The analytical development of the needed coherency detection algorithms and self-sufficient island identification algorithms still needs to be done. There are some research studies which have reported on methods of achieving this objective, but they must be suitable for applying to the California and WECC system in particular. In practical terms, the research and development of algorithms needed has a very good chance of success.

Application of PMU in planned system separation requires consistent dynamic performance of all PMUs. The new IEEE C37.118 standard has recommended but has not specified the required dynamic performance tests for PMUs. This should be resolved for this application. The cost of the project would be substantial, involving PMUs, some new communication facilities, interfaces to trip and block logic in existing relaying schemes, and research on the new methods of detecting instability.

3.3 Applications Roadmap

Deployment of this technology typically involves a large number of entities (utilities in a connected grid, ISOs, regional organizations, regulators). Each owner operator is responsible for a part of the system, and has unique information needs. These systems need to support a wide range of applications for their stakeholders, thus need to accommodate diverse requirements of different applications. Deploying a system that engages multiple users with diverse requirements, varying needs, and different perspectives is a major challenge and requires a common perspective.

A challenge for this study, given that deployment needs depend on regional and individual stakeholder (for example, utility, ISO) requirements and existing infrastructure, that many applications are still in the research and development stage, and that the individual deployment roadmaps (applications and their requirement) are not fully developed, has been to provide a common near, mid, long-term deployment roadmap. Given the nature of PMU implementation requiring broad user participation, this step is necessary to design and deploy the overall PMU system.

Based on an interview process with key stakeholders, this roadmap could serve as a base for development of individual deployment roadmaps and guidance to the vendors to prioritize their developments.

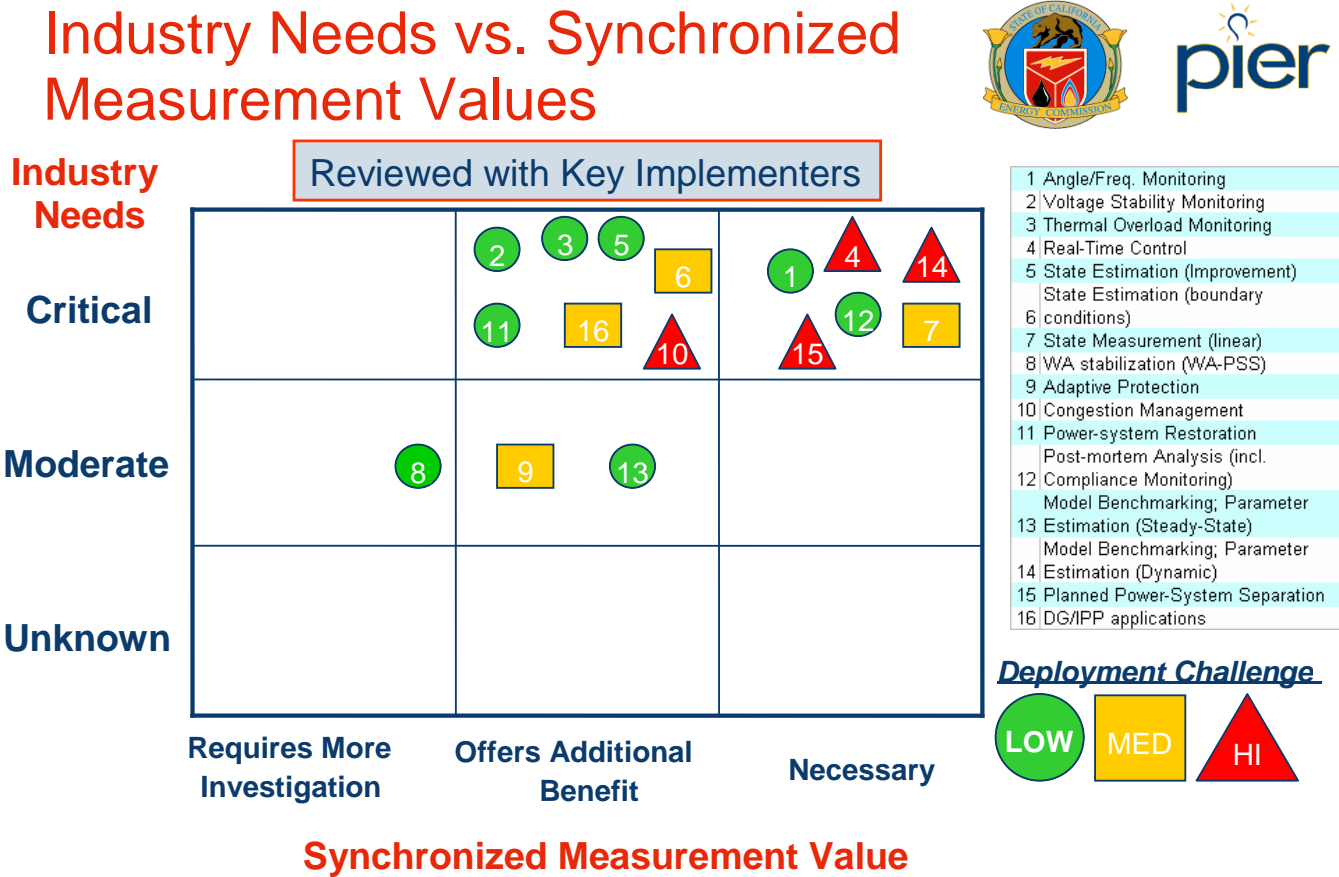
The roadmap presented here is related to technology deployment of the PMU system. It uses as inputs the business needs of an application, the commercial availability and cost, and the complexity with deploying the application.

To arrive at the roadmap, the project team follows the following steps:

- Step 1: Conduct a critical review of PMU applications, summarizing the benefits, the implementation gaps and costs for each application. This is reported in Appendix B, *Application Benefits*.
- Step 2: Discuss results with utility PMU leaders and executives, to understand their system-specific needs and how each application can meet each of those needs. Vendors are also contacted during this step. The document used in this step is the Business-case Evaluation Matrix.
- Table C-1 of Appendix C shows the template that was distributed to a number of utility engineers and managers. The intention of this matrix is to gauge the business needs of each application (regardless of the technology to be used), the role of the PMU to the working of the application, the commercial status of the application, and whether a business case has been built for the application. Participants of the survey can also indicate whether the needs for the application are immediate or long term.
- Individual survey returns are assembled to arrive at a consensus. Table C-2 of Appendix C shows the collective results from the survey.
- Step 3: Use the results of the survey (Table C-2, Appendix C) as a basis; correlate the needs for each application with its commercial status and the complexity of its deployment.

Figure 1 shows the summary on how the technology meets the needs of the industry. First, industry needs (critical, moderate, or unknown) are identified regardless of technology. Secondly, the value of the PMU technology, for each identified application, has been mapped related to importance (necessary, offers additional benefit, requires more investigation) in serving industry needs. Thirdly, deployment challenges (low, medium, high) have been mapped for each application. The deployment challenges are defined based on technology (communications and HW/SW requirements and development status) and applications status (commercially available, pilot installation, in the research phase, not developed yet). Business case examples (Section 3.4.4. and Appendix E), although intended primarily for illustrative purpose, have provided data to create information in Figure 1.

Figure 1: Synchronized Phasor Measurements and Industry Needs



The matrix has provided a basis to create the near, mid, and long-term deployment roadmap. The resulting roadmap is shown in Figure 2, where the applications are grouped into near term (1 year to 3 years), medium-term (3 years to 5 years) or long-term (more than 5 years). This roadmap differs from the RD&D roadmap (for example,, from CERTS/EIPP, Appendix B-1) as it focuses on business and reliability needs to commercialize and deploy PMU technology and applications.

The list of applications in Figure 1 and Figure 2 appears to be larger than the 10 groups reviewed in Section 3.2. This is because some groups in Section 3.2 are broad and need to be subdivided to address specific utility problems. For example, Real-time Monitoring & Control is subdivided into Angle/Frequency Monitoring, Voltage Stability Monitoring, Real-time control and Wide-Area Stabilization.

Applications in the near-term group reflect the reality that the needs are immediate, and the applications are commercially available (either at present time, or will be soon offered by a vendor based on the status of the working prototypes). They also reflect the fact that the deployment can be achieved rather quickly due to factors such as the

applications can be used for specific spots on the grid, and the infrastructure requirements are relatively modest. These applications can be termed “more easily achievable”. The most obvious “more easily achievable” for which PMUs provide major benefits are angle/frequency monitoring and post-mortem analysis (including compliance monitoring).

Applications in the medium-term group largely reflect that even though the needs are great, the commercial prospect is still far off as no working prototypes are known to exist.

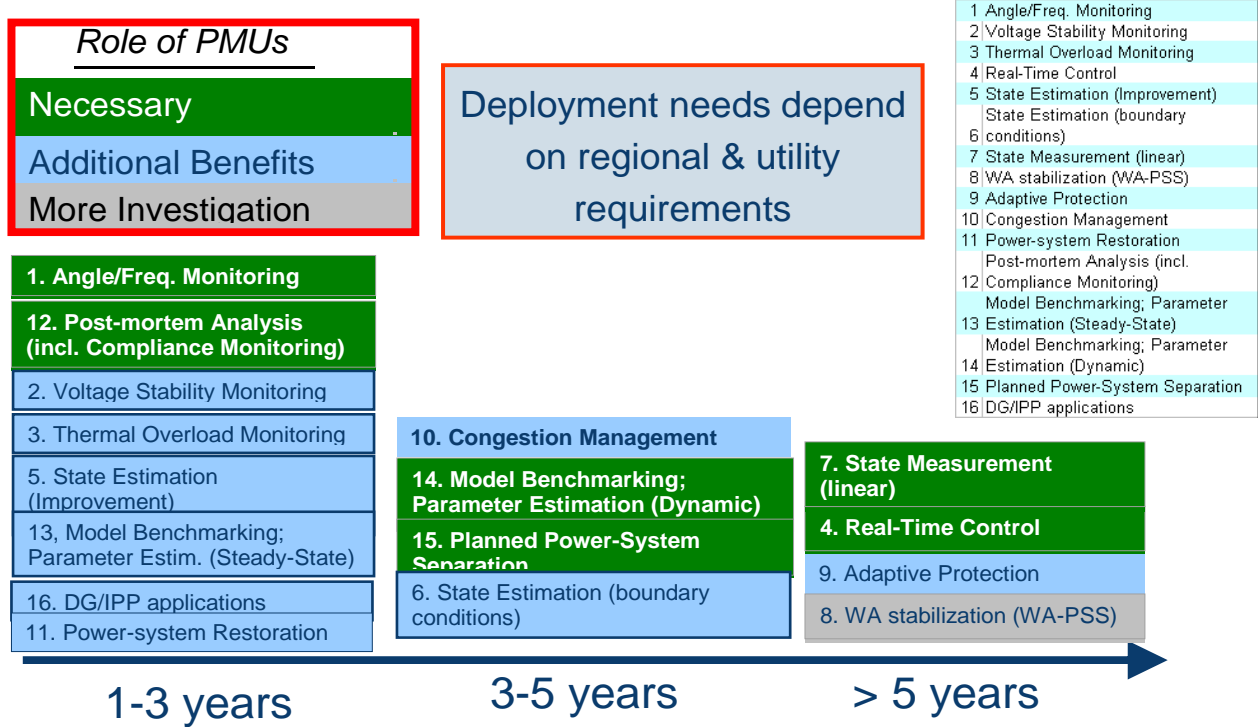
Applications in the long-term group indicate a combination of distant commercial status, extensive infrastructure requirements (and thus costs), and/or that lengthy field trials are required to gain acceptance. (The Wide-area Stabilization application, even though commercially ready, remains to show its superiority to the conventional Power System Stabilizer.)

Of all the applications, six either have a major improvement impact with PMUs or cannot be implemented without PMUs. They are: Angle/Frequency Monitoring, Post-mortem Analysis, Model Benchmarking, Outage Prevention (including Planned Power System Separation), State Measurement and Real-time Control.

As for the rest of the applications, non-PMU technologies are available; however, the deployment of PMUs allows the same measurements to be used to realize additional benefits from the same investment.

Three complementary approaches in using PMU technology with State Estimation – conventional SE improvement (evolutionary), boundary conditions SE, and State Measurement (revolutionary), - are considered to be elements of short to long term PMU deployment strategy using increasing number of PMUs locally and regionally. In fact, the revolutionary case is a natural extension of the evolutionary approach as numbers of PMUs installed continues to increase. Use of PMUs for representing boundary conditions will stem from system-wide regional deployment.

Figure 2: Road Map for Deploying PMU Applications



Based on the Deployment Roadmap of Figure 2, Table 3 below provides a rough estimate of the percentage of full penetration of the Synchronized phasor measurement technology and major applications in utility/ISO planning and operating practices. Some external factors are taken into account, such as rate of upgrades of IEDs and RTUs to incorporate GPS time signal.

Table 3: Estimated Market Penetration

Year	2010	2015	2020 and beyond
Market penetration (%)	15 - 35	30 - 55	50 – 90

3.4 Business Case Analysis Guidebook

3.4.1 Background of the Guidebook

Synchronized phasor measurements represent a next generation of paradigm-shift technology, enabling improvements in planning and operating electrical grids. The companion *Application Benefits* in Appendix B addresses technical benefits that the technology can bring and the practical experience by the industry. At present, related

projects however have been in the R&D stage, and implementers have found it difficult to economically justify a wide-scale deployment.

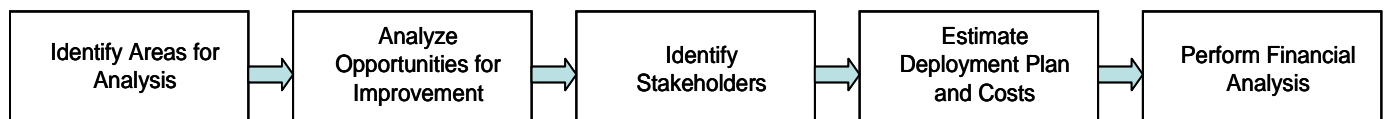
3.4.2 Objective of the Guidebook

This guidebook is intended to provide general guidance for building a business case for the PMU technology. This guide provides a framework and tools for conducting improvement efforts while directing the user to existing info and available support.

3.4.3 Overview of the Guidebook

There are five general phases to do a business case analysis for PMU technology deployment. These phases are summarized in Figure 3.

Figure 3: Business Case Analysis Process



Phase I (Table 4) involves determining the desired state based on the current and projected operating environment. The focus is on understanding performance gaps with the existing technologies and practices, and on understanding what the PMU can help bridging those gaps. The key objective is to identify an organization, function, activity and/or process to improve and to define the criteria for success.

Phase II (Table 5) includes the delineation of issues specific to the organization that can be addressed by the PMU technology. Key activities in this phase include: focusing on the problem area for analysis; collecting data/information to quantify the benefits.

Phase III (Table 6) identifies the stakeholders and the benefits that PMU may mean to them. This is important in the case that the investment must be made by more than one organization. Understanding the benefits to each stakeholder can help articulate the sale of the technology to that particular stakeholder.

Phase IV (Table 7) provides an expected plan for PMU deployment. The deployment typically takes several years, with associated costs for each year.

Phase V (Table 8) compares the projected benefits over a time horizon with the initial investment costs and recurring (annual) costs. A number of project valuation techniques can be used to arrive at a decision of whether the project should start or not.

Table 4: Steps in Collecting Data for Phase I, Identify Areas for Analysis

Steps	Inputs	Outputs	Available Support	Comments
1. List the major functions, activities, processes that Synchronized phasor measurements might help with	Synchronized phasor measurements technical capability;	List of functions, activities, processes	Technical Report of this California Energy Commission project	
2. Identify the current performance of each function, activity, process, ...	Documented performance indicators	List of performance by function, activity, process	Engineering department	
3. Identify existing use of PMU in the industry and experience in enhancing planning and operations.	List of initial targets and list of achieved targets.	List of improvements brought about by PMU. List of unfulfilled goals.	Technical Report of this California Energy Commission project. Public-domain reports, publications, IEEE, IEE, CIGRE. Industry surveys	See Appendix F for a typical industry survey
4. Identify government mandates, if any.	NERC, U.S. DOE, FERC announcements	Required performance and penalty		

Table 5: Steps in Collecting Data for Phase II, Analyze Opportunities for Improvement

Steps	Inputs	Outputs	Available Support	Comments
1. Delineate benefits of PMU to specific activities in your organization	Phase I findings	Organization-specific targets	Engineering Department	
2. Quantify the benefits as (a) direct revenue, (b) avoided cost.	Historical record of events, incidents.	List of pre-PMU cost per event. List of post-PMU (projected) reduction in cost per event	Company's financial record	
3. Identify needed equipment to achieve the benefits	Hardware performance; communications reliability, delays and bandwidth; available applications	Design specification for a system	Engineering department; Industry sources on other PMU projects; Vendors	
4. Prioritize the benefits	List of targets (Step 1)	List of benefits and associated rankings	Management	

Table 6: Steps in Collecting Data for Phase III, Identify Stakeholders

Steps	Inputs	Outputs	Available Support	Comments
1. Identify benefits of PMU to personnel from departments within the organization	Phase II findings	List of improvements	Various departments	
2. Articulate benefits of PMU to identified stakeholders in the organization	Phase II findings. Historical record related to regional incidents: stock-price movement; Litigation costs; Restoration cost; troubleshooting cost	Estimated dollar figures for each benefit		
3. Identify of benefits of PMUs to stakeholders outside the organization	Formulae to estimate benefits due to avoided cost of blackouts	Estimate of PMU benefits for incidents in local area		

Table 7: Steps in Collecting Data for Phase IV, Estimate Deployment Plan and Cost

Steps	Inputs	Outputs	Available Support	Comments
1. Estimate capital costs	Phase II findings (List of components and associated costs)	List of components to deploy per year; List of costs of these components.	CERTS publication; Vendors	See Appendix G for estimated component costs
2. Estimate variable costs	List of expected upgrades, maintenance of system	Annual costs	Past EMS projects, IT projects	
3. Form alternatives	Phase II findings (Step 1). Priority list (Phase II, Step 4)	List of alternative deployment plans, and associated costs.	Company's business plan	
4. Sketch deployment plans	Output from Step 3	Number of years for deployment, and list of annual expectations	Vendors, consultants	

Table 8: Steps in Collecting Data for Phase V, Perform Payback Analysis

Steps	Inputs	Outputs	Available Support	Comments
1. Form projection of quantified benefits	Phase II findings; Phase III findings; Economic trends and rates	List of benefits per year for each stakeholder; discounted rate, growth rates (of annual expense, load)	Accounting dept.	Benefits can be cost savings, avoided costs, hour savings, or direct revenue
2. Form projection of capital investment and annual expenses	Phase IV findings (esp. Steps 3-4)	List of expenditure per year	Accounting dept.	
3. Evaluate project alternatives	Deployment plans (outputs from Step 4, Phase IV); outputs from Steps 1-2	Go/No Go decisions	NPV, Modified NPV, Real Options	Use NPV; If negative NPV, use modified NPV or Real Options

To address the first four steps, a questionnaire such as that in Appendix F, Sample survey for collecting data as input for Business Case Analysis Technical Experience with PMU devices, can be used as the starting point to collect data. A 2005 published report from CERTS (CERTS, 2005) can also be consulted for cost estimates of various elements of a deployment.

Business techniques to decide if a project should be pursued that are used in this study and are recommended for the user are described below:

- NPV (Net Present Value). In this traditional approach, one projects all future benefits, expenses and needed investment for a number of years. The numbers are discounted to present time and are summed to produce the Net Present Value. The project gets a Go when NPV is positive. Simple probabilistic elements are sometimes used in conjunction with the traditional NPV, as the modified NPV. For example, one might consider three scenarios: optimistic, pessimistic, and average.
- Real Options Analysis (ROA). This method takes the modified NPV one step further by taking into account the probabilities of the projected benefits. ROA is suitable for phased investments, and is particularly suitable for PMU projects as they are deployed over several years. In an example, it takes 4 years to build up the project. For each year, as the knowledge about the perceived benefits becomes clearer, the management has the option of stopping the project, postponing or expanding it. ROA is used when NPV results are negative, yet the project is deemed strategic enough that the management finds it necessary to conduct a phased approach; they will capture the upside should favorable

scenarios develop over the course of time. In an illustrative example (Appendix E), the deployment of a PMU system to improve Congestion Management yields negative NPV. Since in the proposal phase of the project, there is a considerable uncertainty with the benefits (Congestion Management is a new application), Real Options is used to value that uncertainty and the management flexibility during the course of the project.

It is left to the user to decide which technique would better fit concrete needs.

3.4.4 Examples and Recommendations

Examples of how the Guidebook is used are given in Appendix E. Even though the quantitative numbers were based on an interview with a utility company, they are primarily for illustrative, test purposes. More detailed, fully developed analysis is required for a rigorous and accurate business case analysis. In any case, this study helped draw some general conclusions:

- A multiple-purpose deployment is the means to reap major benefits from the PMU technology. This is because the same capital investment can be used by different subject areas, stacking up the benefits. This kind of deployment, however, requires a careful analysis and planning as the capital investment is high.
- A partial deployment (or ad hoc) that targets a limited objective is suitable for R&D. Lacking a careful plan for integrated use of the infrastructure, several partial deployments when combined at a later time can be costlier than a full deployment.
- Partial deployments, when evaluated individually in the proposal phase, are likely to show poor or unacceptable payback. However, if a partial deployment is an initial phase for a full-deployment scheme, Real Options Analysis is a recommended method for project valuation. This technique takes into account two elements that the traditional NPV does not: (a) the uncertainty in the projected benefits, and (b) the management flexibility to stop the project or to expand it into next phases.

A brief summary of the quantitative results is described next. Details are presented in Appendix E.

Identified applications are grouped into common subject areas:

- Outage Prevention
- Post-mortem Analysis, which can be deployed with or without Outage Prevention.
- Congestion Management

The following deployment plans have been analyzed:

Case 1 Full deployment of above identified applications.

Case 2 Partial deployment with Post-mortem Analysis only, with the following assumptions:

- The cost is the base deployment.
- Conservative assumptions, including only time saved, but not stock-price change, avoided costs, and avoided outages due to better preparation (in some cases only possible by using PMU data).

Case 3 Partial deployment with Outage Prevention and Post-mortem analysis with following assumptions:

- The cost is base deployment, equipment upgrade and annual costs.
- Conservative assumptions, including lost revenue and restoration costs, but not stock-price change and avoided costs.
- Preventing catastrophic blackouts (from 1 event in 5 yrs. to 1 in 10).
- Reducing disturbances due to voltage excursions (from 3 to 1 event/yr.).
- Enhanced RAS arming study (from 6 to 2 events/yr.).

Case 4 Partial deployment with Congestion Management only. The cost is base deployment, software applications, and annual costs.

Results of those illustrative, test business cases are summarized in Table 9.

Table 9: Summary of Illustrative Business Case Results

Case	NPV Results (k\$)
1. Full deployment	43,667 - 317,759 ³
2. Post-mortem Analysis only	-78
3. Outage Prevention and Post-mortem analysis only	19,023 – 314,932 ⁴
4. Congestion Management only	1,258 (using ROA)

Case 2 clearly shows that calculating business benefits for partial deployment with partial benefits may result in misleading conclusions. For a large disturbance the size of 2003 Northeast blackout, NERC allocated 2-3 people on a 75 percent time working over 9-10 months. Based on NERC estimates, it is expected that with PMUs, this resource requirement would be 1-2 months with 2-3 people full time. One can expect that affected utilities devoted much more person-hours to the effort. The collective savings with PMUs would justify the cost of investing in a large number of PMUs. Such a detailed benefit analysis, however, is beyond the scope of this project.

3.5 System Architecture and Deployment Gaps

Implementing a large-scale PMU system presents some unique challenges. Such systems need to transmit and store large amount of data. Deployment of this technology typically involves a large number of entities (utilities in a connected grid, ISOs, regional organizations, regulators). Each owner/operator is responsible for a part of the system. These systems need to support a wide range of applications for their stakeholders and thus need to accommodate diverse requirements by various applications. Various applications have different requirements on the number of PMUs, data-reporting rate, data accuracy and reliability, and so forth. For example, an out-of-step relay using PMU data may need only two PMUs with very high data-reporting rate and communications reliability. A State-Estimator using PMU data may need hundreds of PMUs to achieve a major performance improvement, but need a much slower data rate.

As many applications are still in the research and development stage and the deployment roadmaps are not fully developed, requirements are not clearly defined. This is one of the main reasons that there is a lack of available products to support large-scale implementation. How to design a system that meets all those diverse requirements under current situations is a major challenge and the key to the deployment success. Ensuring the consistent performance of all PMUs that will be acquired from multiple vendors, and installed, operated and maintained by different entities is another major challenge.

³ Two different estimates are due to different ways the costs of blackout/outage are estimated: GDP (lower figure), LBNL (higher figure).

⁴ ibid.

While the applications area is still in the development phase, PMU hardware is based on proven technology. Phasor measurement technology was developed near the end of 1980's and the first products appeared on the market in the early 1990's. Presently, a significant number of vendors are offering PMUs. Most of the products are either based on existing platforms or have PMU functionality added to the existing platforms by simply adding hardware, such as a GPS receiver, to achieve accurate time stamping, and in some cases, by adding required communication interfaces (if they do not already exist). Technology required for the necessary communication infrastructure already exists as well,

Although benefits of using PMU technology are evident and the key technologies are available, the main hurdles for applying PMU technology are in:

- PMU device procurement, installation, operation, and maintenance cost.
- Packaging and productization of communication and integration infrastructure required for PMU applications. This challenge is further increased by the need to build a system-wide architecture.

Regarding the former, using existing IED platforms with integrated PMU functionality or by planned integration of stand-alone PMUs in enterprise level communication and data management infrastructure reduces overall deployment costs. The retrofit/upgrade approach using IEDs with integrated PMU functionality makes it easier and less costly to make improvements requiring PMU functionality in future applications. Also, one can expect that in the near future there will be thousands of IEDs in operation with built-in PMU functions. Although there are concerns with implementing PMUs in devices like protective relays, those issues could be overcome with the following:

- Test performance of integrated devices under fault conditions using defined guidelines. For example, the EIPP Performance Requirement Task Team is developing a guideline that is planned to become a NERC standard and is coordinated with IEEE 37-118 standard activities (http://phasors.pnl.gov/resources_performance.html).
- Define standard procedures (data collection, communications, security, and so forth) and responsibilities for commercial O&M of PMU systems, including:
 - PMU installation, commissioning, and maintenance
 - Access to data and setting and set-up changes
 - Security procedures and issues
 - Needs for separate access by various groups

In some cases, it may still be beneficial to use stand-alone PMUs. In general, where the PMU function should reside depends on various factors (applications and their requirements, communication architecture, upgrade requirements, and so forth).

In any case, when such IEDs reach a critical mass, there will be a paradigm shift in applying synchronized phasor technology in power systems. The challenge will be in how to use those IEDs and their associated software applications more effectively to improve the system operation, and to achieve desired financial benefits. This trend requires that special attention be paid to the PMU system architecture. Even now, the main cost is with the system components, such as data concentrators, the software applications, and the supporting communications systems.

An ideal PMU system architecture should properly address the following issues:

- Scalability: As the number of installed PMUs and IEDs with integrated PMU functions increase gradually, the system architecture must be designed so that it can keep up with this trend.
- Flexibility: As many of the system components will be acquired, installed, operated and maintained by different entities, the system architecture should be very flexible to accommodate the diverse requirements of these entities.
- Communications bandwidth and latency: In the new paradigm, on-going communications cost (if leased from communications service providers) could become the main cost item of a PMU system. Reducing the bandwidth requirement will help to reduce the on-going cost of PMU applications. Minimizing the communication bandwidth requirement will also help to reduce the latency of the PMU data transferring. For real-time applications, reducing the communication latency is a must.
- Ease with adding/removing PMUs/IEDs and enabling/disabling PMU applications: To accommodate the growth of IEDs with PMU functionality, the architecture must be so that it is easy to add a new device to the PMU system. Occasionally, devices need to be taken off-line, such as for routine maintenance; their temporary removal should be accomplished easily and should not hamper related applications. Similarly for the software side, the design should also allow easy enabling or disabling applications when needed.

Existing RD&D projects are striving to achieve the above-mentioned features, such as the GridStat initiative to design the next-generation communications system for the power grid⁵. However, in practice, there is still a large gap to overcome as PMU systems today are designed to accommodate near-term needs. They are small systems consisting of one data concentrator and a few PMUs.

Currently, there are some efforts, notably the WECC and EIPP projects in the U.S., to connect small PMU systems implemented by individual utilities together to form a larger system. Yet, the total number of installed PMUs is still well below 100 for each system. The number of installed PMUs is projected to increase to a few hundreds in next

⁵ GridStat, information available on-line: <http://www.gridstat.net>

few years for these two systems. Both systems use their master data concentrators developed in-house by BPA and TVA respectively, due to lack of commercial products at the time these systems were started and developed.

The EIPP system uses a master data concentrator to aggregate the PMU data either from PMUs directly or indirectly from connected utility data concentrators, and then re-transmit aggregated PMU data back to utility data concentrators. The system architecture may not meet the requirements of the optimal system and is facing the challenge that the weakest link in the system is determining a performance of the system. As the number of installed PMUs grows, the system may have difficulties to keep up with the demand. Relying on utility data concentrators to relay PMU data not only adds time delays, but also make it difficult for the system to accommodate the growing number of applications. It is likely that the number of installed PMUs and IEDs will quickly out-grow the capacity of the master data concentrators. Lack of vendor support is also a major concern.

An obstacle to wide-area implementation of PMUs is that vendors are reluctant to develop system components, such as data concentrators for substations and control centers, as there is no clear specification for an accepted system architecture and the related system components. The market demand for such system components is not clear to vendors.

To facilitate a large-scale deployment of PMUs in California/WECC and to meet the diverse requirements of different applications, there is a need to design, specify, and develop an optimal architecture. An optimal system architecture would provide a solid foundation for implementing a California and WECC PMU system that is highly scalable, flexible, easy to operate and maintain, and requires minimal communication bandwidth and low latency. The chosen architecture should generate clear specifications of various system components. The specifications will help vendors to develop products to allow shared use of PMU data among various applications, and to meet the performance requirement of each application.

PMU deployment at California/WECC is at the stage when it is necessary to design, specify, and develop an optimal architecture that will serve present and future application needs for the whole western grid. As more effort and money is spent on individual utility systems in California/WECC, it becomes more important to deploy a common California/WECC PMU system connecting utility systems to take full advantage of the PMU technology.

CHAPTER 4:

Recommendations and Conclusions

4.1 Recommendations and Key Success Factors

Although this study identifies that PMU technology provides major tangible and intangible benefits to various stakeholders, transfer to commercial implementation has not been easy so far. Even utilities that have led the industry in installing PMUs through early RD&D projects are still in the process of technology transfer.

Major success factors for technology transfer are summarized below:

- Even though individual utilities will benefit from local implementation, full benefits are realized through regional and grid-wide deployment. System-wide deployment requires implementing common system architecture and data sharing (not easy to accomplish in the de-regulated environment).
- Major benefits will be realized after deploying the basic infrastructure, as benefits of adding new applications are far bigger than incremental costs of new applications. This also requires utilities to set up operational and business processes to support short to long term technology deployment.
- Even though a number of vendors provide PMU HW products, one obstacle to wide-area implementation of PMUs is that vendors have not developed either key applications or other system components (such as fully productized high performance data concentrators). The market demand for applications and system components needs to be clear to vendors. Vendors will be less reluctant to invest in developing a full product portfolio if there are clear specifications for industry application priorities and required system architecture.
- Economic regulation must provide mechanism to support investments in the technology that will result in full benefits of implementing the technology grid wide.

In conclusion, to gain the benefits offered by this technology to the U.S. Western grid and the overall industry, a coordinated effort among utilities, the California ISO and WECC must be undertaken. This requires an effort that includes a bottom-up approach from utilities in defining the needs, applications and uses of PMUs and an top-down approach from the system operators and coordinators to define an integrated specification, architecture and operational scheme to optimize the benefits offered by the technology.

The following process is proposed to the industry to speed up and minimize costs of deployment.

- Each PMU user in the grid should develop a near-, mid-, and long-term application/technology deployment roadmap. This roadmap would include

application requirements that would guide PMU installations and system architecture needs locally and regionally.

- NERC/ERO and/or WECC should champion required data exchange and the development of the overall system infrastructure to facilitate achieving benefits of deploying key application (for example, more easily achievable applications emphasized in the study). Based on individual user requirements, it is necessary to develop system architecture design, specification, and deployment plan. All users connecting to the overall architecture would need to fulfill key integration requirements (HW /SW interoperability, data quality, and so forth). It is also beneficial to prioritize applications from the grid perspective.
- Develop uniform requirements and protocols for data collection, communications, and security through standards (NERC, IEEE, WECC, EIPP). Engage vendors in standard development and provide clear requirements for both accepted system architecture and industry application priorities.
- Regulators at both federal and state levels need to provide incentives for technology deployment, particularly considering significant benefits for rate payers and transmission system reliability.
- Each user should set up operational and business processes for installations, operations, maintenance, and benefits sharing. This would comprise of creating projects with defined deliverables and deadlines; identifying asset owner, manager, and service provider; setting up procedures and rules; educating and training users; and facilitating culture change.
- Continue investing in R&D (U.S. DOE, PIER, vendors, users, and so forth) and promote developing and sharing test cases to develop new applications. Continue using a proven approach of pilot projects to gain experience and confidence.

Only by having all the stakeholders contributing will this promising technology fulfill its' promise for achieving financial and reliability benefits. Those benefits will be accomplished only by significant market penetration of this technology that is dependent on vendors developing required products. If commitment from key stakeholders (for example, PAC, regulators) on the extent of PMU system implementation, including providing application and architecture requirements, is communicated to the vendors, they will be able to achieve return on investment required to build key applications and system components.

4.2 Conclusions

As transmission grid upgrades are planned, designed and implemented for the future, phasor measurement technology should be an integral part of the specification and design to enhance overall operational reliability. This independent study has concluded that the synchronized phasor measurement technology is necessary to improve the

safety, reliability, and efficiency of the grid. This study has concluded that there are large reliability and financial benefits for customers/society and the California and WECC electrical grid, thus providing motivation for regulators to support deployment of this technology and its' applications. In addition, individual utilities could realize financial benefits if several integrated applications are deployed using basic PMU system infrastructure. These conclusions have been reached through comprehensive analysis of various applications and related benefits, concrete data on PMU system related costs and benefits, and industry experience with PMU implementation.

The technology of PMUs is a known quantity. Many implementations and demonstrations around the world (with California and WECC utilities representing some of the industry leaders) have verified the capability of the technology to provide synchronized, time-stamped information about system conditions. This information offers operators the opportunity to avoid catastrophic outages, improve system utilization, and accurately assess and predict the status of the system under varying conditions. The level of technological readiness does vary, however, across the various applications that may be addressed through PMUs. For example, the use of PMUs for real time monitoring and control has been proven by a number of utilities and can be considered ready for commercial operations. Similarly, PMU data for post-mortem outage analysis offers much greater efficiency and accuracy in determining root causes of blackouts. It is realized that accurate event analysis may not even be possible without PMUs. Other applications, however, require more development and testing before working prototypes can be developed and implemented.

A challenge to the industry in harvesting benefits offered by PMUs is in the movement from a research and development environment to commercial operation. Although working prototypes are proven for some applications and can be implemented with relatively small efforts, the lack of commercialization of the technology inhibits full-scale implementations. Operational and business processes and models have not been developed in most companies to address all the issues associated with the implementation of this technology and therefore, the move to operational status is restricted. Further, the lack of a system architecture developed at the ISO or Regional Coordinating Council level to guide implementation in a consistent and coordinated manner is an issue that prevents utilities from investing in the technology. Without question, the specification for a system implementation must be an integrated, cooperative effort between utilities and the operating and coordinating entities.

As PMU projects can involve significant costs in infrastructure and technology, the identification of quantifiable benefits can facilitate the acceptance and funding of projects. Benefits for PMU applications fall into tangible and intangible categories and, depending upon the financial evaluation practices of a utility, can vary widely. Tangible benefits can be derived from the increased quantity and quality of data provided through PMU applications that facilitate better utilization of system capacity, more efficient use of manpower, and improved reliability of operations. In many cases the first cost of implementation will not be offset by the tangible operational benefits but

through incremental applications and capabilities provided by PMU technology, the direct benefits grow considerably.

Most compelling however are the benefits that come in less tangible form. These include the avoided costs associated with outage investigation, blackout recovery costs, and avoided costs of political and regulatory activities following major system events. Also not to be overlooked are the costs associated with market perception of utility capability and the associated stock value impact that can result from negative publicity. Finally, on a larger scale, are the societal costs associated with system blackouts resulting in lost productivity as well as lost opportunity for economic expansion. This study has raised awareness that major potential financial benefits may be realized in using PMUs in market operations, such as congestion management and accurate LMP pricing.

It is the conclusion of this study that phasor measurement capability is advanced technologically to the point that commercial implementation of selected applications is both possible and warranted. Further, the implementation and use of this capability is necessary for the levels of grid operational management that are required for efficient use of the infrastructure currently in place as well as for infrastructure enhancements of the future. To gain the benefits offered by this technology, a coordinated effort among utilities, the California ISO and California and WECC must be undertaken. Without a system-wide approach, the capabilities and associated benefits will not be achieved in the manner possible. This requires an effort that includes a bottom-up approach from utilities in defining the needs, applications and uses of PMUs and an top-down approach from the system operators and coordinators to define a integrated specification, architecture and operational scheme to optimize the benefits offered by the technology.

This study recommends guidelines to realize benefits of this paradigm shifting technology. The general near-, mid-, and long-term application/technology deployment roadmap, developed through analysis of financial benefits of various applications, deployment challenges, and interviews with key stakeholders and industry leaders, serves as a base to guide users and vendors in taking appropriate actions for transition to commercial operation. For example, “more easily achievable” applications – for which needs are immediate, PMUs are required, and infrastructure requirements are relatively modest - are angle/frequency monitoring and visualization, and post-mortem analysis.

It is recommended that each user creates an application deployment roadmap that will guide PMU installations and system architecture needs. If required, the business case guidebook could support creation of this application deployment roadmap. As a part of the deployment process, users need to initiate projects including setting up operations and maintenance procedures and rules and training users.

As a large number of applications are in initial stage and there are potential new applications, it is necessary to continue investing in RD&D (U.S. DOE, PIER, vendors, users, and so forth). RD&D roadmap by EIPP and CERTS and deployment roadmap

from this study are important to provide structured and consistent directions that would focus efforts, avoid unnecessary duplication, and optimize RD&D investments. Very successful practice of joint pilot projects needs to continue to gain experience and confidence.

Finally, commitment from key stakeholders (for example, PAC, regulators) on the extent of PMU system implementation needs to be communicated to the vendors so they could develop their development roadmaps (for key applications and system components) with expected return on investment

Glossary

AESO	Alberta Electric System Operator
AIES	Alberta Interconnected Electric System
BPA	Bonneville Power Administration
California ISO or CalISO	California Independent System Operator
Energy Commission	California Energy Commission
CERTS	Consortium for Electric Reliability Technology Solutions
CIEE	California Institute for Energy and Environment
COI	California-Oregon Interties
DA	Day Ahead
DG	Distributed Generation
DMWG	Disturbance Monitoring Work Group of the WECC
U.S. DOE	United States Department of Energy
DSA	Dynamic Signal Analyzer
DSI	Dynamic System Identification
EIPP	Eastern Interconnection Phasor Project
EMS	Energy Management System
EPG	Electric Power Group
EPRI	Electric Power Research Institute
ERO	Electric Reliability Organization
FACTS	Flexible AC Transmission System
FACRI	Fast AC Reactive Insertion
FFT	Fast Fourier Transform
FPA	Fast Prony Analysis
FRR	Frequency Regulating Reserves
GE	General Electric
GPS	Global Positioning System
GUI	Graphic User Interface
HA	Hour Ahead
HSVC	High Side Voltage Control
HVDC	High Voltage DC (Direct Current)
IED	Intelligent Electronic Device
IPP	Independent Power Producers

LMP	Locational Marginal Pricing
M&VWG	Monitoring & Validation Work Group of the WECC
MW	Megawatts
NERC	North American Electric Reliability Council
NPV	Net Present Value
NTC	Nominal Transfer Capability
PDC	Phasor Data Concentrator
PE	Parameter Estimate (or Estimation)
PG&E	Pacific Gas & Electric
PIER	Public Interest Energy Research
PMU	Phasor Measurement Unit
PNNL	Pacific Northwest National Laboratory
PPSM	Portable Power System Monitor
PSLF	Positive Sequence Load Flow
PSM(1)	Power System Monitor (primary definition)
PSM(2)	Power System Measurements (secondary definition)
PSPS	Power System Protection Schemes
RAS	Remedial Action Scheme
ROA	Real Options Analysis
RT	Real Time
RTDMS	Real Time Dynamic Monitoring System
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SCIT	Southern California Import Transmission
SCE	Southern California Edison
SE	State Estimation (Estimate)
SDG&E	San Diego Gas & Electric
SIPS	System Integrity Protection Schemes
SPA	Standing Phase Angle
SRP	Salt River Project
SVC	Static VAR Compensator
TCSC	Thyristor-Controlled Series Capacitor
TRP	Transmission Research Program
TVA	Tennessee Valley Authority

UTCE	Union for the Co-Ordination of Transmission of Electricity
WACS	Wide Area Stability Control System
WAMPAC	Wide Area Monitoring, Protection and Control
WAMS	Wide Area Measurement System
WAPA	Western Area Power Administration
WECC	Western Electricity Coordinating Council
WeSDINet	Western System Dynamic Information Network
WPF	Wind Power Facilities
WSCC	Western Systems Coordinating Council

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